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PLANE STRAIN FRACTURE TOUGHNESS FOR HANDBOOK PRESENTATION

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Materials Research and Development
Equipment Laboratories
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PLANE STRAIN FRACTURE TOUGHNESS DATA
FOR
HANDBOOK PRESENTATION

E. A. Steigerwald

FOREWORD

This report was prepared by Dr. E. A. Steigerwald of the Materials Research and Development, TRW Equipment Laboratories, TRW Inc., 23555 Euclid Avenue, Cleveland, Ohio under Contract No. AF 33(615)-5001. The contract was initiated under Project No. 7381, "Materials Applications", Task No. 738106, "Design Information Development". All work was performed under the direction of Mr. Sidney O. Davis, Project Engineer, Air Force Materials Laboratory.

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This technical report has been reviewed and is approved.

D. A. Shinn, Chief
Materials Information Branch
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ABSTRACT

An experimental program was conducted to determine the plane strain fracture toughness (K_{IC}) of the following classes of high-strength materials:

1. AISI Alloy Steels (4340, 4140)

2. 5 Cr - Mo - V Steels

3. Precipitation-Hardening Stainless Steels (17-7 PH, PH 15-7 Mo, 17-4 PH, AM 355)

4. Titanium Alloy, Ti-6Al-4V

The precracked notched bend test was used as the test method and several heats of each material were evaluated over a range of test temperatures from -100 to +200°F. The K_{IC} values, obtained under conditions which were believed to provide valid plane strain fracture toughness numbers, were compiled for possible presentation in handbook form. The method of presentation involved plotting K_{IC} both as a function of material strength and test temperature. The resulting curves provide representative K_{IC} figures which can aid in the selection of materials for reliable performance.

(Distribution of this abstract is unlimited).

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SECTION I

INTRODUCTION

In selecting ultra high-strength materials for high strength-to-weight application, the designer must give considerable attention not only to the smooth strength capabilities of the material but must also evaluate the reliability of the material in terms of its resistance to brittle crack propagation. Although the need for a definitive criterion to rate the brittle fracture susceptibility of a material has long been recognized, the development of suitable test methods which yield quantitative design parameters has only recently been developed (1)*. These test methods, which are based on fracture mechanics concepts, produce an evaluation parameter thatcan be obtained from simple laboratory tests and subsequently used to predict the load-carrying capacity of full-size components.

The availability of fracture mechanics, along with the confidence obtained through current usage, has made it possible for a plane strain fracture toughness parameter (K_{IC}) to be considered for handbook presentation. Prior to this time, handbook data have been restricted to conventional smooth strength properties since the common parameters used to define material reliability, such as notch tensile strength or impact energy are dependent on specimen geometry and are not material constants. On this basis a notch toughness parameter could at best provide only a relative indication of material properties and then only if the specimen geometries were comparable. The fracture toughness parameter (K_{IC}) however, can in principle be obtained from a number of different test methods and provide a meaningful material constant.

The purpose of this program was to provide fracture toughness data (K_{IC}) for selected alloys so that the values could be considered for presentation in handbook form as a standardized material rating parameter. Emphasis was placed on experimentally determining K_{IC} values for materials and test temperature regions that are not currently available.

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* Numbers in parentheses pertain to references on Page 44.

SECTION II

MATERIALS AND PROCEDURE

The materials selected for the test program are summarized in Table 1 along with code designation, the form, and the handbook reference. Specimens from at least two heats of each type of material were evaluated over a range of test temperatures from -100 to +200°F. The compositions of the test materials are given in Table 2 along with the vendor and heat number. The method of heat treatment and the room temperature smooth strength properties obtained from the treatment are summarized in Table 3.

The smooth tensile properties of each of the material variables were determined using specimens having the configurations shown in Figure 1. The tests were conducted at a crosshead speed of 0.01 in/min. which was equivalent to a 0.01 in/in/min. strain rate in the smooth tests and an increase in nominal stress between 100,000 and 10,000 psi/min. in the notch tests.

Notch bend tests on precracked specimens were used to determine the plane strain fracture toughness (K_{IC}). During the initial phases of the program, four-point loading was employed in accordance with the method described in AFML-TR-65-213 (2). When the ASTM practice involving three-point loading was published (3), the test method was changed to be in accord with this recommendation. The specimen geometry is summarized in Figure 2 along with the formulae used to calculate K_{IC}. Precracking of the specimens was performed at room temperature after heat treatment by tension-tension loading as a cantilever beam using a peak stress that was approximately 20% of the yield strength and a loading frequency of 1800 cpm.

The current ASTM-recommended practice (3) involves using a chevron notch as a crack starter and a final crack depth-to-width ratio (a/W) of 0.5. In addition, a clip-type displacement gage which fits directly into the notch is suggested for maximum crack detection sensitivity (5). Previous test recommendations however involved a straight-sided crack starter and an (a/W) ratio of approximately 0.2. Deflectometers using linear voltage differential transformers placed on the loading arms were also used to detect the point where plane strain crack growth is initiated rather than the more sensitive clip gage.

During the course of the test program, the methods summarized in Table 4 were employed to measure K_{IC}. In selected instances the methods were compared on the basis of the effect of crack size and the method of crack detection (LVDT deflectometer placed on the loading arm versus displacement gage placed in the notch).

A critical factor in determining K_{IC} is selecting the load (P) which corresponds to a finite degree of crack growth to provide a definitive K_{IC} value. The practice used for selecting the load in this program, conformed to that recommended by ASTM, and is shown schematically in Figure 3. The curve types designated as Class III involved specimens where the initiation of slow crack growth corresponded to total specimen failure. In this case, the load displacement curves showed no deviation from linearity and comparable results were

TABLE 1

MATERIALS IN TEST PROGRAM

Alloy	Code	Heats	Material Form	Test Temperature (°F)	Target Strength(FTU)Ksi or Treatment	Thickness	Reference in MIL Handbook 5
4340	1	A, B, and C	Plate	-100 to 200	260	3/8"	2.3.1.1
4340	2	A. B. and C	Plate	-100 to 200	200	1" dia.	2.3.1.1
4140	3	A, B, and C	Bar	-100 to 200	200	1" dia.	2.3.1.1
5Cr-Mo-V	4	A, B, and A'	Plate	-100 to 200	260	1/2"	2.5.1.1
5Cr-Mo-V	5	B	Bar	-100 to 200	275	1/2"dia.	2.5.1.1
5Cr-Mo-V	6	A	Bar	-100 to 200	240	1" dia.	2.5.1.1
17-7 PH	7	A, B, and C	Plate	-100 to 200	TH 1050	1/2"	2.7.2.1
17-7 PH	8	A, B, and C	Plate	-100 to 200	RH 950	3/16"	2.7.2.1
17-7 PH	9	A, B, and C	Plate	75	RH 950	1/2"	2.7.2.1
17-7 PH	10	A, B, and C	Bar	75	RH 950	1"	2.7.2.1
PH 15-7 Mo	11	A, B	Plate	-100 to 200	TH 1050	1/2"	2.7.3.1
PH 15-7 Mo	12	A, B	Plate	-100 to 200	RH 950	1/2"	2.7.3.1
PH 15-7 Mo	13	A, B	Bar	75	TH 1050	1"	2.7.3.1
PH 15-7 Mo	14	A, B	Bar	75	RH 950	1"	2.7.3.1
17-4 PH	15	A, B	Plate	-100 to 200	H 900	1/2"	2.7.4.1
17-4 PH	16	A, B	Bar	75	H 900	1/2"	2.7.4.1
AM 355	17	A, B	Plate	-100 to 200	SCT 1000	1/2"	MIL-S-88408
AM 355	18	A, B	Plate	75	SCT 1000	1/2"	MIL-S-88408
AM 355	19	A, B, C	Bar	-100 to 200	SCT 1000	1"	AMS-5743 and AMS-5744
Ti-6Al-4V	20	A, B, C	Plate	-100 to 200	165	1/2"	5.4.6.1

TABLE 2

ALLOY COMPOSITIONS

Alloy	Code	Vendor	Heat No.	C	Mn	P	S	Si	Cr	Ni	Al	Cu	Mo	Ta	V
4340	1A	Republic	3920569	.43	.84	.006	.005	.27	.78	1.78			.26		
4340	1B	*	45927	.41	.69	.018	.012	.29	.78	1.87			.22		
4340	1C	*	335285	.40	.75	.005	.010	.29	.79	1.77			.25		
4340	2A	Vasco	08290	.43	.69	.010	.004	.31	.81	1.83			.28		
4340	2B	*	45927	.41	.69	.018	.012	.29	.78	1.87			.22		
4340	2C	*	3352385	.40	.75	.005	.010	.29	.79	1.77			.25		
4140	3A	Lukens	B4706	.38	.81	.008	.025	.27	.91				.17		
4140	3B	Reliable	74-P-646	.40	.82	.014	.019	.25	.92				.17		
4140	3C	Lukens	B4582	.37	.75	.010	.019	.26	.85				.15		
5Cr-Mo-V	4A,4A'	Vasco	31207	.39	.31	.016	.010	.90	4.91				1.30		0.51
5Cr-Mo-V	4B	**		.35	.37	-	-	.84	4.87				1.23		0.61
5Cr-Mo-V	5A	Vasco	31207	.39	.31	.016	.010	.90	4.91				1.30		0.51
5Cr-Mo-V	5B	**		.35	.37	-	-	.84	4.87				1.23		0.61
5Cr-Mo-V	6A	Vasco	33015	.38	.35	.010	.007	.96	4.99				1.36		0.50
5Cr-Mo-V	6B	**		.35	.37	-	-	.84	4.87				1.23		0.61
17-7PH	7A	+	56044	.08	.75	.011	.013	.26	16.9	6.85	1.30				
17-7PH	7B	Armco	890483	.076	.66	.019	.007	.32	17.0	7.17	1.22				
17-7PH	7C	+	36050-2A	.078	.62	.023	.008	.25	16.9	7.38	1.36				
17-7PH	8A	+	35384-1A	.069	.63	.017	.012	.36	17.2	7.29	1.08				
17-7PH	8B	Republic	3332623	.077	.78	.032	.013	.50	16.7	6.90	1.11				
17-7PH	8C	Republic	3570616	.073	.72	.028	.005	.43	16.7	7.20	1.05				
17-7PH	9A	+	56044	.080	.75	.011	.013	.26	16.9	7.85	1.30				
17-7PH	9B	Armco	890483	.076	.66	.019	.007	.32	17.1	7.17	1.22				
17-7PH	9C	+	36050-2A	.078	.62	.023	.008	.25	16.9	7.38	1.36				
17-7PH	10A	Republic	3570591	.072	.68	.028	.005	.64	17.3	7.10	.90				
17-7PH	10B	"	3343953	.073	.74	.024	.005	.69	16.8	6.95	1.14				
17-7PH	10C	"	3541962	.075	.82	.027	.005	.48	17.2	7.25	.95				

TABLE 2 (Continued)

Alloy	Code	Vendor	Heat No.	C	Mn	P	S	Si	Cr	Ni	Al	Cu	Mo	Ta	Cb
PH-15-7Mo	11A,12A	+	61631	.070	.61	.012	.009	.60	15.3	7.71	1.28		2.30		
PH-15-7Mo	11B,12B	+	810047	.070	.52	.018	.012	.26	15.1	7.31	1.19		2.37		
PH-15-7Mo	13A	**		.055	.75			.39	14.5	7.33	1.15		2.16		
PH-15-7Mo	13B	**		.060	.74			.38	14.6	7.43	1.22		2.21		
PH-15-7Mo	14A	**		.055	.75			.39	14.5	7.33	1.15		2.16		
PH-15-7Mo	14B	**		.060	.74			.38	14.6	7.43	1.22		2.21		
17-4PH	15A	+	64404	.036	.24	.018	.016	.58	15.8	4.31		3.46		.02	.21
17-4PH	15B	+	64706-1	.037	.28	.019	.013	.60	15.7	4.37		3.29		.01	.21
17-4PH	16A	+	64872	.038	.22	.018	.018	.64	15.7	4.27		3.46		.01	.21
17-4PH	16B	+	55980	.035	.21	.017	.014	.51	15.7	4.38		3.10		.01	
AM 355	17A	Al-Lud	W23422	.113	1.08	.012	.006	.32	15.08	4.06			2.82	.093	N_2
AM 355	17B	Al-Lud	W24515	.121	1.08	.017	.005	.24	15.46	4.22			2.66	.072	N_2
AM 355	18A	Al-Lud	W23422	.113	1.08	.012	.006	.32	15.1	4.06			2.82	.093	N_2
AM 355	18B	Al-Lud	W24515	.121	1.08	.017	.005	.24	15.46	4.22			2.66	.072	N_2
AM 355	19A	+	W25490	.125	.88	.02	.008	.20	15.1	4.34			2.87	.084	N_2
AM 355	19B	+	W23586	.108	.99	.01	.004	.37	15.3	4.18			2.55	.078	N_2
Ti6Al-4V	20A	*	292457	.020							6.2		4.2V	.15Fe	
Ti6Al-4V	20B	*	301483	.030							6.5		4.3V	.16Fe	
Ti6Al-4V	20C	*	D7651	.026							6.3		4.3V	.15Fe	

+ Supplier is Aluminum Mill Supply Corp.

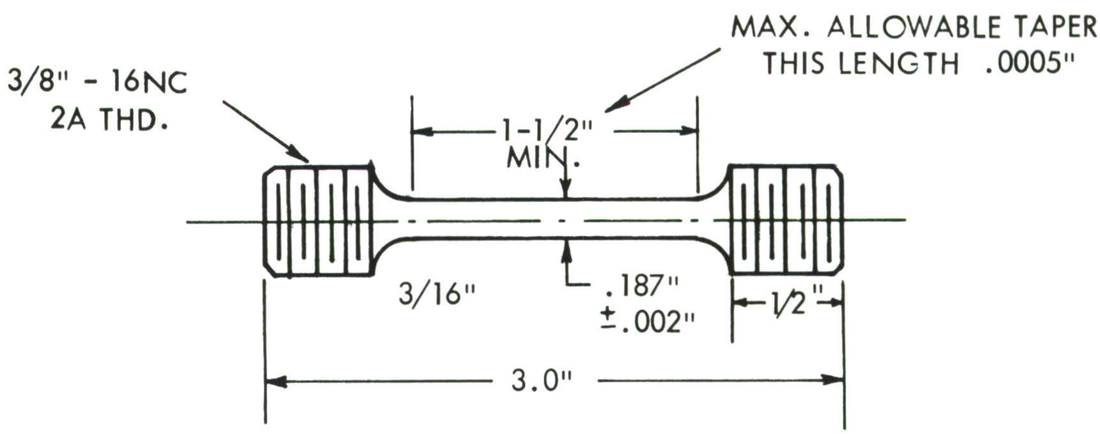
* Supplier is Aluminum for Aircraft Corp.

** Supplied by TRW Stock

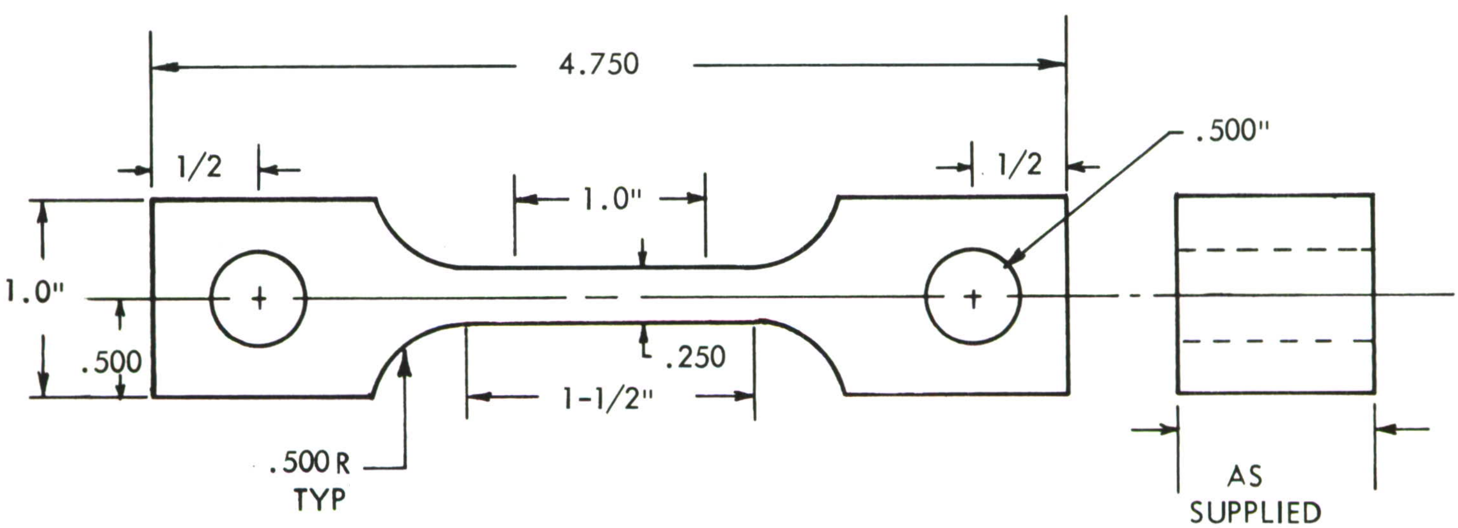
TABLE 3

Summary of Heat Treatments

Material	Code	Heat Treatment*	Average Room Temperature Strength F_{TU}(ksi)	F_{TY} (ksi)
4340	1A, 1B, 1C	Aust. 1550°F Salt, OQ, Temper 1 hr. + 1 hr. at 500°F	260	220
4340	2A, 2B, 2C	Aust. 1550°F Salt, OQ, Temper 1 hr. + 1 hr. at 800°F	210	197
4140	3A, 3B, 3C	Aust. 1550°F Salt, OQ, Temper 2 hrs at 800°F	205	190
5Cr-Mo-V	4A, 4B, 4A'	Aust. 1850°F Salt, OQ, Temper 1 hr. + 1 hr.at 1080°F	260	212
5Cr-Mo-V	5A, 5B	Aust. 1850°F Salt, OQ, Temper 1 hr. + 1 hr. at 1030°F	275	-
5Cr-Mo-V	6A, 6B	Aust. 1850°F Salt, OQ, Temper 1 hr. + 1 hr. at 1100°F	240	200
17-7PH	7A, 7B, 7C	1400°F, 90 min; cool to 550°F; age 1050°F for 90 min.	182	167
17-7PH	8A, 8B, 8C	1750°F, 10 min; cool to -110°F for 8 hours; age 950°F-1 hr.	185	167
17-7PH	9A, 9B	1750°F, 10 min; cool to -110°F for 8 hours; age 950°F-1 hr.	198	181
17-7PH	10A, 10B	1750°F, 10 min; cool to -110°F for 8 hours; age 950°F-1 hr.	222	208
15-7Mo	11A, 11B	1400°F, 90 min. ; cool to 55°F; age 1130°F for 90 min.	194	191
15-7Mo	12A, 12B	1400°F, 90 min. ; cool to 55°F; age 1050°F for 90 min.	233	205
15-7Mo	13A, 13B	1400°F; 90 min. ; cool to 55°F; age 1130°F for 90 min.	178	-
15-7Mo	14A, 14B	1400°F; 90 min. ; cool to 55°F; age 1080°F for 90 min.	186	175
17-4PH	15A, 15B	Cool to 55°F; age 900°F for 1 hour	194	168
17-4PH	16A, 16B	Cool to 55°F; age 900°F for 1 hour	207	194
AM 355	17A, 17B	Anneal 1710°F, WQ; cool -100°F, 3 hrs; age 1000°F- 3 hrs.	176	164
AM 355	18A, 18B	Anneal 1710°F, WQ; cool -100°F, 3 hrs; age 1000°F- 3 hrs.	174	165
AM 355	19A, 19B	Anneal 1710°F, WQ; cool -100°F, 3 hrs; age 1000°F- 3 hrs.	179	167
Ti6Al-4V	20A, 20B, 20C	Solution treat 1700°F, air cool, age 1000°F- 4 hrs.	167	162

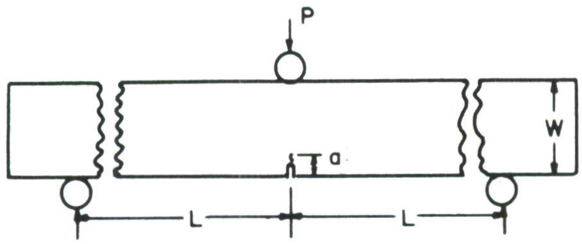


BAR AND PLATE SPECIMEN



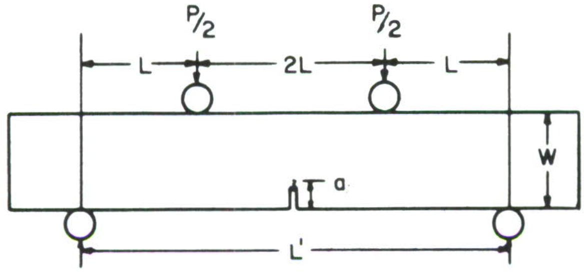
SHEET SPECIMEN

FIGURE 1 GEOMETRY OF SMOOTH TENSILE SPECIMENS



$$K_{IC}^2 = \left(\frac{P}{B}\right)^2 \frac{L^2}{W^3} \left[31.7 \frac{a}{W} - 64.8 \left(\frac{a}{W}\right)^2 + 211 \left(\frac{a}{W}\right)^3 \right]$$

NOTCH BEND TEST (THREE - POINT LOADING)



$$K_{IC}^2 = \left(\frac{P}{B}\right)^2 \frac{L^2}{W^3} \left[34.7 \frac{a}{W} - 55.2 \left(\frac{a}{W}\right)^2 + 196 \left(\frac{a}{W}\right)^3 \right.$$

NOTCH BEND TEST (FOUR - POINT LOADING)

$$a = a_o + \frac{K^2}{6\pi \sigma_{YS}^2} \text{ IN ALL CASES}$$

FIGURE 2 FORMULAE USED TO COMPUTE K_{IC} VALUES (REF. 4)

TABLE 4

Summary of Methods Used to Determine K_{IC} with the Notch Bend Test

Material	Code	Type of Loading	Crack Starter*	Nominal Crack depth (a/w)	Method of Detection
4340	1	3-pt.	CV, SS	0.50; 0.20	Clip gage
4340	2	4-pt.	SS	0.20	Deflectometer
4140	3	4-pt.	SS	0.20	Deflectometer
5Cr-Mo-V	4	3-pt.	CV, SS	0.50; 0.20	Clip gage
5Cr-Mo-V	5	3-pt.	CV, SS	0.50; 0.20	Clip gage
5Cr-Mo-V	6	3-pt.	CV, SS	0.50; 0.20	Clip gage
17-7 PH	7	4-pt.	SS	0.20	Deflectometer
17-7 PH	8	4-pt.	SS	0.20	Deflectometer
17-7 PH	9	4-pt.	SS	0.20	Deflectometer
17-7 PH	10	4-pt.	SS	0.20	Deflectometer
15-7 Mo	11	4-pt.	SS	0.20	Deflectometer
15-7 Mo	12	4-pt.	SS	0.20	Deflectometer
15-7 Mo	13	3-pt.	CV, SS	0.50; 0.20	Clip Gage
15-7 Mo	14	3-pt.	CV, SS	0.50; 0.20	Clip Gage
17-4 PH	15	3-pt.	CV, SS	0.50; 0.20	Clip Gage
17-4 PH	16	3-pt.	CV, SS	0.50; 0.20	Clip Gage
AM 355	17	3-pt.	CV, SS	0.50; 0.20	Clip Gage
AM 355	18	3-pt.	CV, SS	0.50; 0.20	Clip Gage
AM 355	19	4-pt.	SS	0.20	Deflectometer
Ti6Al-4V	20	3-pt.	SS	0.20	Clip Gage

* CV signifies chevron crack starter; SS indicates straight-sided crack starter

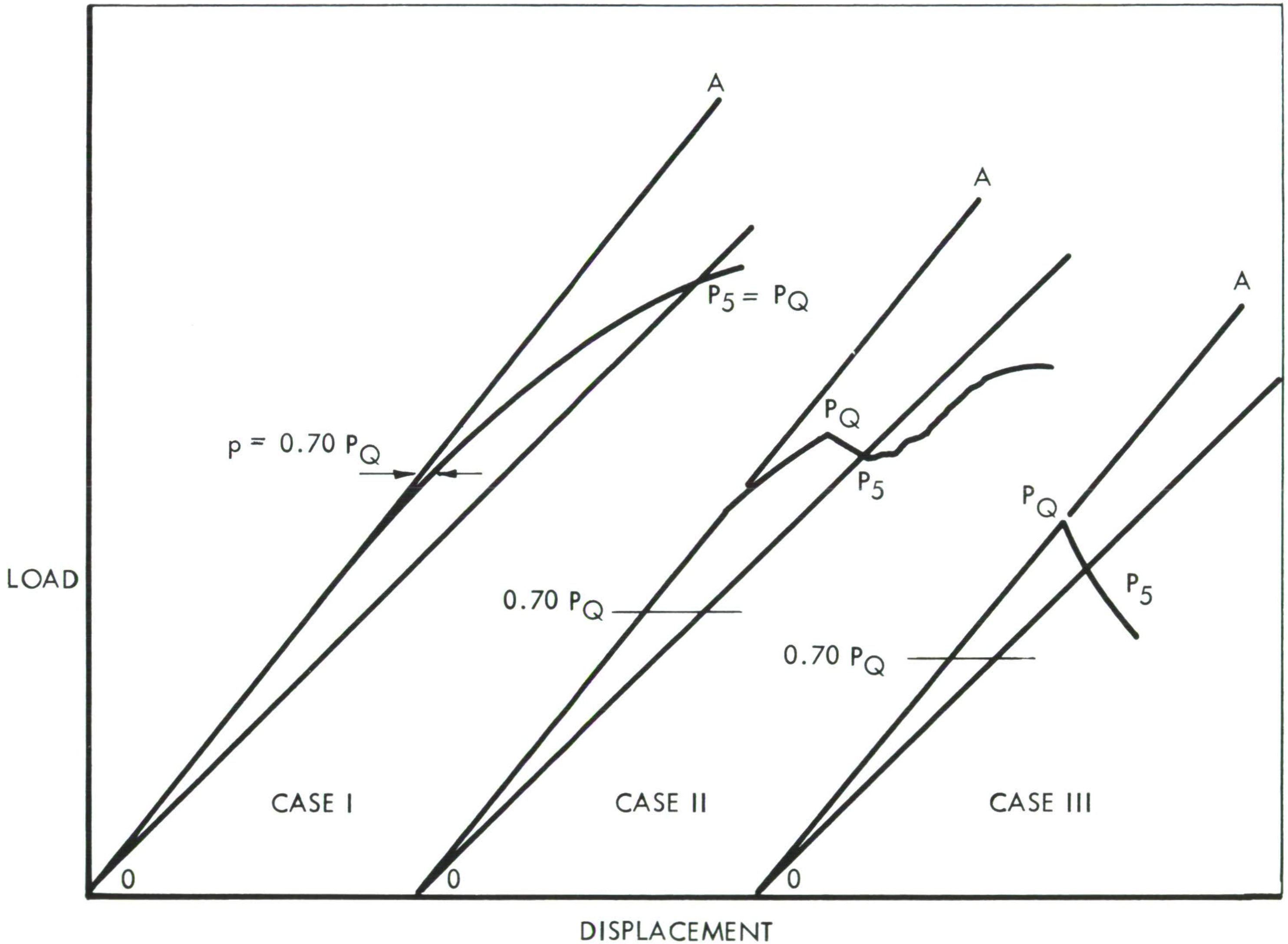


FIGURE 3 REPRESENTATIVE LOAD - DISPLACEMENT RECORDS (SLOPES OP_5 ARE EXAGGERATED FOR CLARITY)

obtained with both the LVDT deflectometer placed on the loading arm and the beam gage placed in the notch. In the case of the curve types designated as Class I or Class II, a secant line (OP_5 in Figure 3) was drawn through the origin with a slope 3% less than the tangent OA. If the load on every point on the record which preceded P_5 was lower than P_5, then P_5 was used to determine K_{IC} provided that the deviation of the OP_5 from OA was less than 1/4 at a point which was 0.7 of P_5. If this latter condition was not met, then the fracture toughness value was not considered valid. If a load existed which was greater than P_5, then this maximum load was used to calculate K_{IC}. Since these criteria are still open to further discussion, the method used to determine the K_{IC} value was recorded in the tabular presentation of the data. A comparison between the LVDT placed on the loading arm and the beam gage in the notch for Class I type curves indicated that the beam gage provided increased sensitivity. From a test parameter standpoint, the K_{IC} values obtained from the Class I curves were approximately 4% lower when the beam gage was employed. In the case of the Class II curves no difference in the selected load for calculating K_{IC} was observed as a function of pick-up method.

The measurement of valid plane strain fracture toughness (K_{IC}) values is dependent on using a specimen with sufficient size so that the plastic zone at the crack tip is relatively small with respect to the overall dimensions of the specimen. A relatively large quantity of data is available which indicates that in the notch bend test, the specimen width (B) should be > 2.5 times the square of the fracture toughness-to-yield strength ratio $(K/F_{TY})^2$ (1,2). The second criterion with respect to specimen dimensions deals with the crack size (a). Although the ASTM recommendation is that $a > 2.5\ (K/F_{TY})^2$, data exist which indicate that if $a > (K/F_{TY})^2$, the fracture toughness deviates by less than 5% from the values obtained with $a > 2.5\ (K/F_{TY})^2$ (6). In the presentation of the experimental data, the tables giving the calculated fracture toughness will also present the $(K/F_{TY})^2$ ratio. In the plotted curves, only those fracture toughness values which have been obtained under conditions were $B > 2.5\ (K/F_{TY})^2$ and $a > (K/F_{TY})^2$ were considered as valid K_{IC} numbers. In every case where the crack growth curve did not conform to the conditions for validity, the specimen size also did not conform to the required range so that the use of the geometrical requirements was a sufficient condition for rejection of invalid values.

At both the low and high temperatures, notch bend tests were performed by submersing the specimen and fixture in either a acetone dry ice bath or a mineral oil bath heated by an immersion heater. The smooth tensile tests below room temperature were conducted by placing the test rig in a cold box where the temperature was maintained by liquid nitrogen vapor automatically controlled by the thermocouple output through a low temperature solenoid. At temperatures above room temperature, the smooth tests were conducted in a resistance-heated furnace.

SECTION III

RESULTS AND DISCUSSION

The detailed presentation of the tests results is given in Tables A-1 through A-37 in the Appendix and the data are summarized graphically in Figures 4 through 23. For purposes of discussion and subsequent presentation in a format for possible handbook use, the materials were categorized according the the following classifications:

(1) AISI Alloy Steels (4340,codes 1 and 2; 4140, code 3),

(2) 5 Cr-Mo-V Steels (Mod H-11, codes 4, 5, and 6),

(3) Precipitation-Hardening Stainless Steels (17-7PH, codes 7, 8, 9, and 10; PH 15-7 Mo, codes 11, 12, 13, and 14; 17-4 PH, codes 15 and 16; AM 355, codes 17, 18, and 19),

(4) Titanium Alloy (Ti6Al-4V), code 20).

1. AISI Alloy Steels

The fracture toughness of the 4340 steel, heat treated to a 220 Ksi yield strength is presented in Figure 4. Although all heats of material showed similar fracture toughness, there was a tendency for heat B to have K_{IC} values slightly below heats A or C. The fracture toughness of the 4340 at a room temperature tensile strength of approximately 210 Ksi is shown in Figure 5. At this strength level, the K_{IC} values at test temperatures of 75 and 200°F were not considered valid because of insufficient crack length. At the lower temperatures, considerably greater differences in K_{IC} were observed between heats than was apparent in the higher strength level material with heat B showing the lowest values. The 4140 steel (Figure 6) exhibited toughness values that were generally lower than those obtained in the 4340 heat treated to the same strength level.

In the case of the tests conducted on 4340 steel, heat treated to the 220 Ksi yield (code 1), both the chevron crack starter with an a/W ratio of approximately 0.5 and straight-front crack starter with an a/W ratio after precracking of approximately 0.2 were evaluated. Representative specimen profiles along with the K_{IC} values are shown in Figure 7. The results indicate that when sufficient crack size is present, both methods provide comparable toughness values.

2. 5 Cr-Mo-V Steel

The data for the 5 Cr-Mo-V steel, heat treated to room temperature, tensile strength levels of 275, 260 and 240 Ksi are presented in Figures 8, 9, and 10. Due to the low toughness of the material at the higher strength levels, considerable problems were encountered with quench cracking and with total failure during the fatigue precracking operation. The agreement in K_{IC} between heats A and B at the 260 Ksi tensile strength level was good. In addition, excellent agreement was also obtained between specimens designated 4A and $4A^1$ which were taken from the same heat but heat treated in different batches to the same strength level. A comparison between the 5 Cr-Mo-V and the 4340 steel at both the 260 and 240 Ksi room temperature tensile strength levels indicates the superior toughness of the 4340.

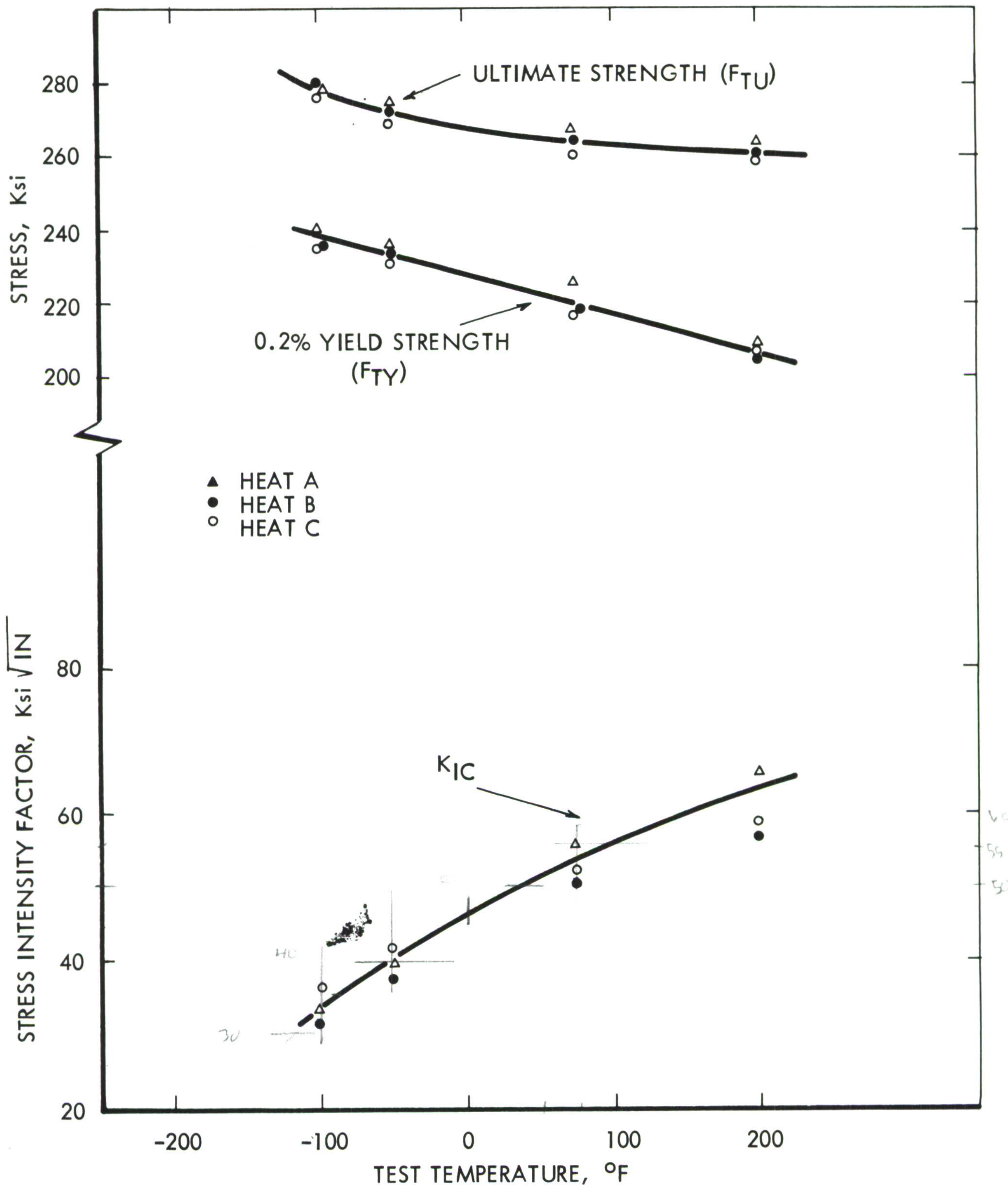


FIGURE 4 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 4340 STEEL, CODE 1.

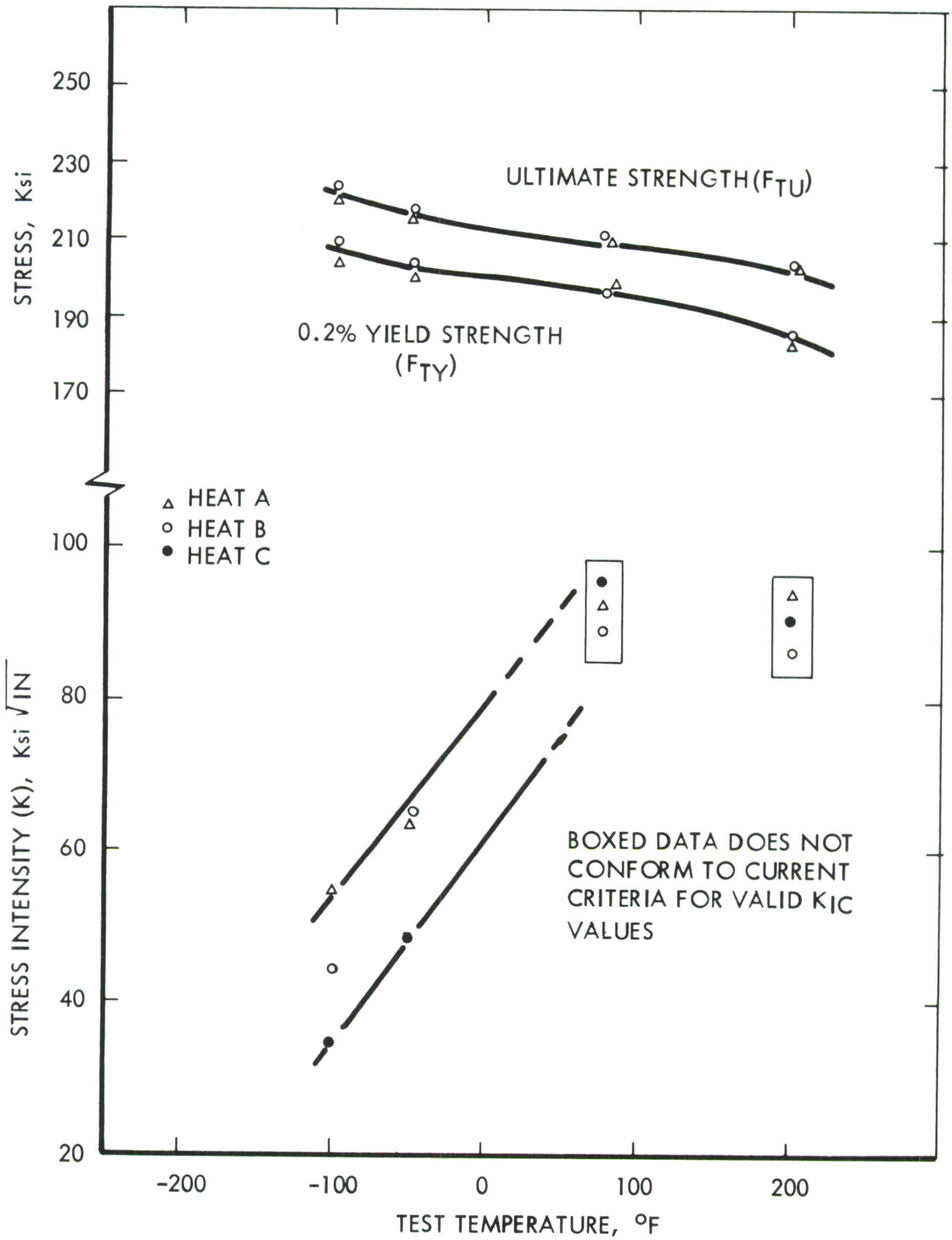


FIGURE 5 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 4340 STEEL, CODE 2.

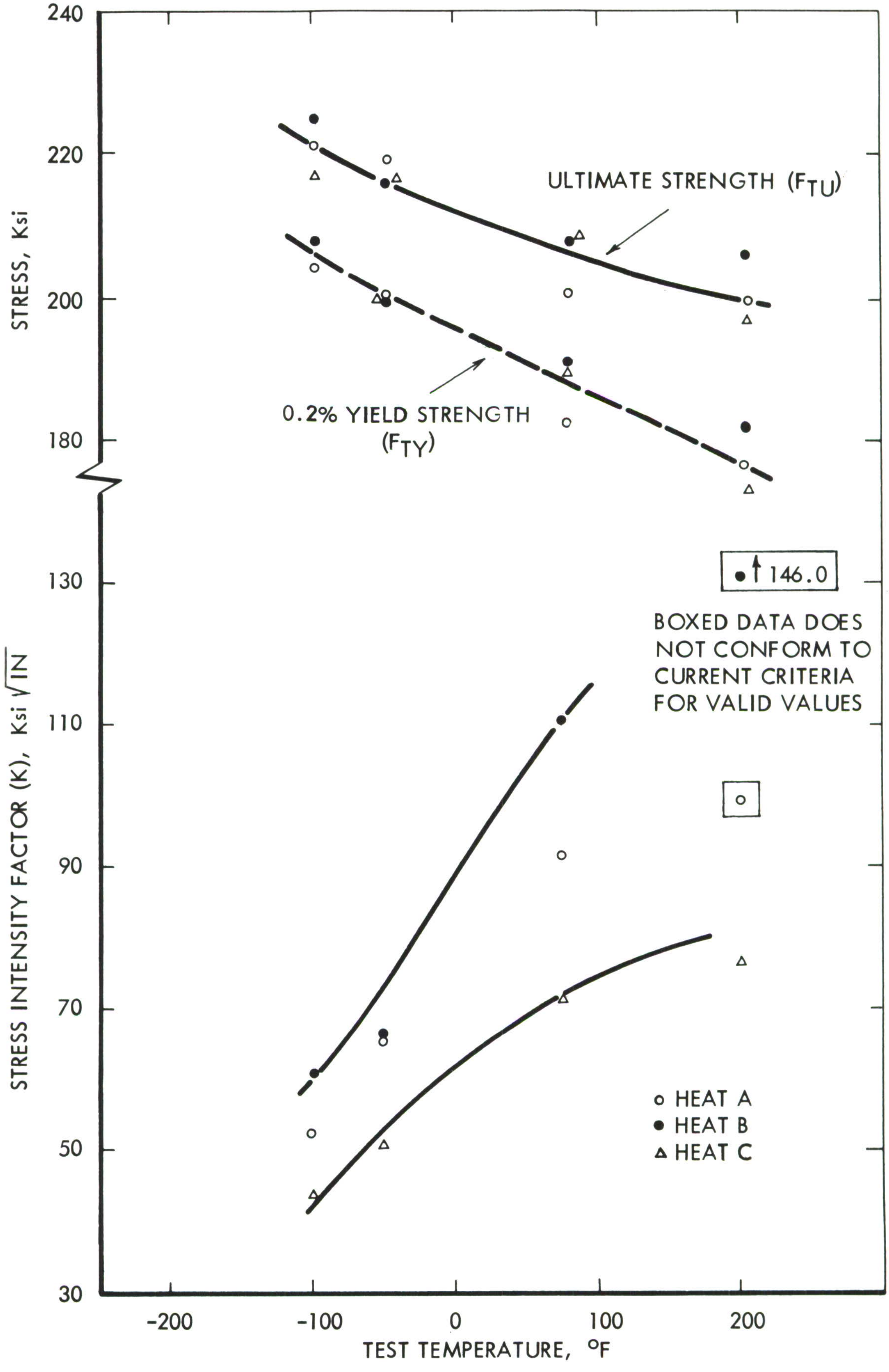
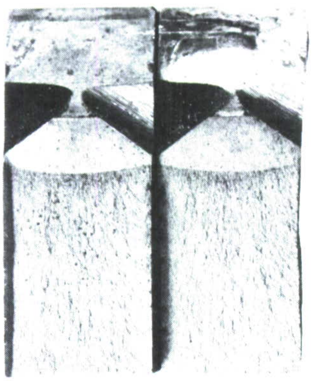
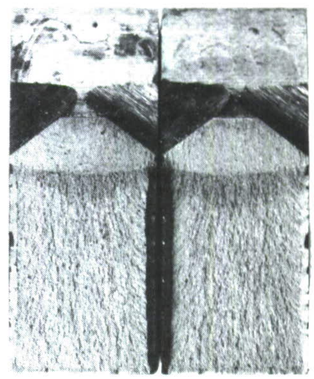


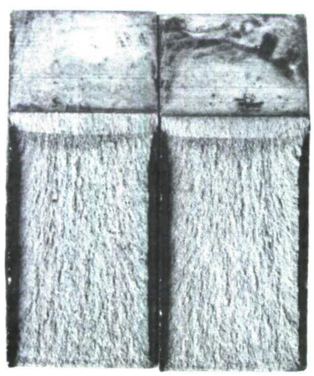
FIGURE 6 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 4140 STEEL, CODE 3.



SPECIMEN 1A71
K_{IC} 53.5 Ksi $\sqrt{IN.}$



SPECIMEN 1A72
K_{IC} 53.5 Ksi $\sqrt{IN.}$



SPECIMEN 1A73
K_{IC} 50.9 Ksi $\sqrt{IN.}$

FIGURE 7 EFFECT OF VARIOUS CRACK STARTER PROFILES ON K_{IC} VALUES, 4340 STEEL, CODE 1, 2X

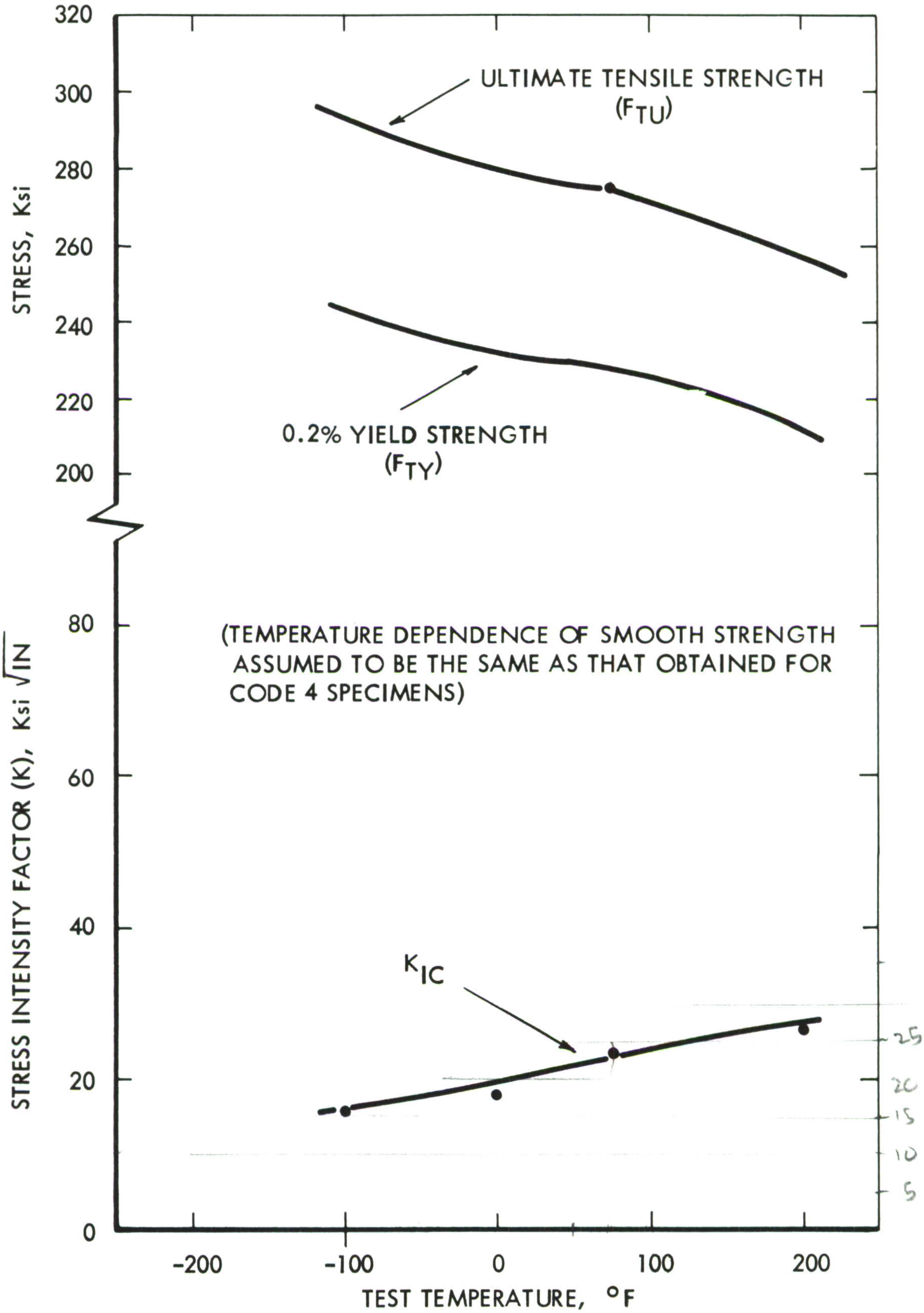


FIGURE 8 FRACTURE TOUGHNESS OF 5 Cr-Mo-V STEEL, CODE 5

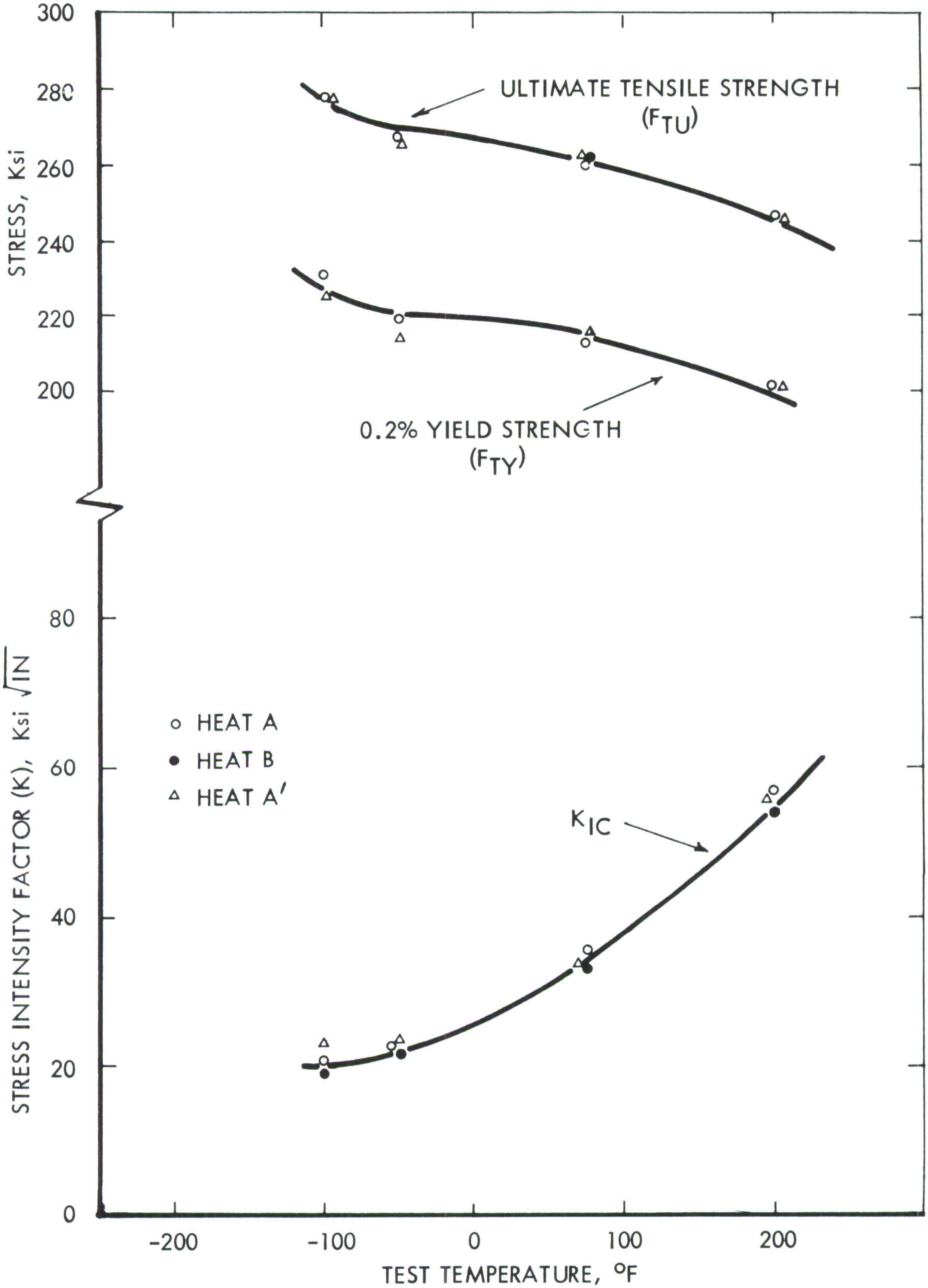


FIGURE 9 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 5Cr-Mo-V STEEL, CODE 4.

718 B

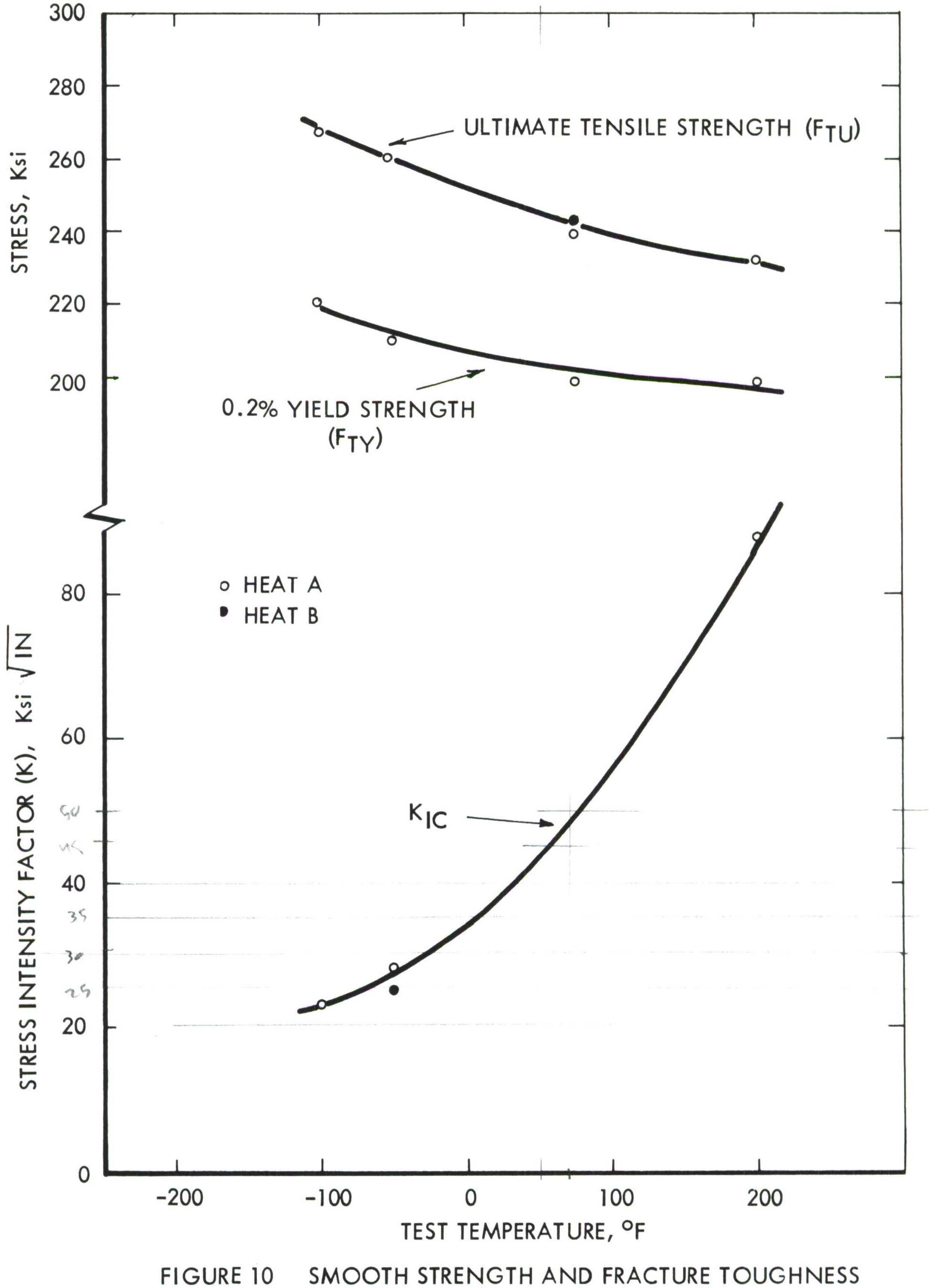


FIGURE 10 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 5Cr-Mo-V STEEL, CODE 6.

726 B

3. Precipitation-Hardening Stainless Steel

Data for the 17-7 PH type of precipitation-hardening stainless steel are given in Figures 11 through 14 (codes 7 through 10). Many of the toughness results, particularly at the lower strength levels, cannot be considered as valid K_{IC} values due to insufficient specimen thickness or crack length. In the plotting of the data those values which did not satisfy the criteria for valid K_{IC} were clearly indicated by a "boxed" symbol. The fracture surface of the precipitation hardening stainless steels often exhibited a strong tendency for internal delamination presumably as a result of the presence of free ferrite. Typical examples of these delaminations are shown in Figure 15. In general, the fracture toughness was greater in the specimens which exhibited the larger degree of delamination probably as a result of the decreased constraint produced by the internal free surface. In some cases the degree of delamination varied with position of the specimen within the plate and this factor contributed to the scatter in K_{IC} between replicate specimens. For example, specimen 7C7-1 exhibited a Class III curve (total failure at maximum load) and had a K_{IC} value of 64.0 Ksi $\sqrt{in.}$ A replicate specimen 7C7-2 however showed a Class I type curve and had a K_{IC} of 101.4 Ksi $\sqrt{in.}$ The fracture surface of 7C7-1 showed no internal delamination while specimen 7C7-2 exhibited considerable splitting along the fracture path. In this case a direct correlation was present between the degree of delamination present on the fracture surface and the fracture toughness value.

Smooth strength and fracture toughness values for the PH 15-7Mo steel are given in Figures 16, 17, and 18. The K_{IC} at the RH 950 condition was almost half that obtained at the TH 1050 treatment. The results indicate the strong dependence of the K_{IC} value on heat treat condition in the precipitation-hardening stainless steels.

The data for 17-4 PH and AM 355 stainless steels are given in Figures 19, 20, and 21. As in the case for the PH 15-7 Mo Steel, the 17-4 PH toughness showed a rather significant decrease between 75 and -50°F and little additional variation when the testing temperature was further decreased to -100°F. Much of the data obtained for the AM 355 steel did not produce valid K_{IC} values due to insufficient specimen size.

The variation of room temperature plane strain fracture toughness with tensile strength is shown in Figure 22 for the precipitation-hardening steels in plate form. The data for the 17-7 and 15-7 defined a consistent relationship while the results obtained on the 17-4 were significantly below the average curve. In the case of the 17-7 and 17-4, the specimens obtained from bar stock (codes 10 and 16) produced K_{IC} values considerably above those obtained for the plate material. In the test conducted with the 15-7 Mo, the reverse was true. In the 15-7 Mo no delamination in the fracture surface was present in the bar material and on this basis, the lower fracture toughness may be due to a decrease in free ferrite concentration.

If the data obtained for the 17-7 or 15-7 steels at -100 or -50°F is plotted on Figure 22 using the smooth strengths obtained at the specific test temperatures, then the K_{IC} is considerably below that defined by the room temperature curve. On this basis, the decrease in fracture toughness which occurs as a function of test temperature cannot be explained solely on the basis of the increase in smooth strength properties.

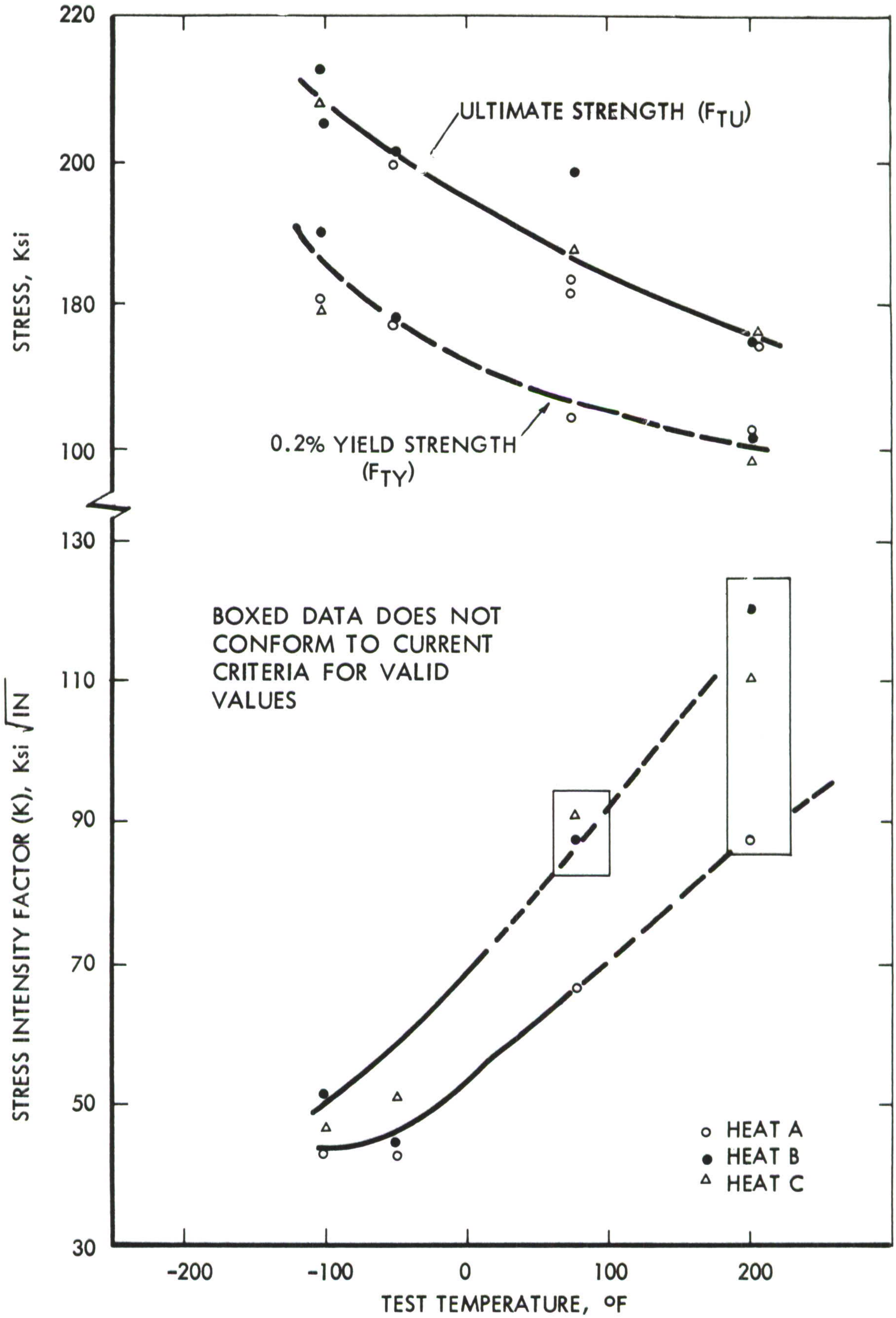


FIGURE 11 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 17-7 PH STEEL, CODE 7, TH 1050.

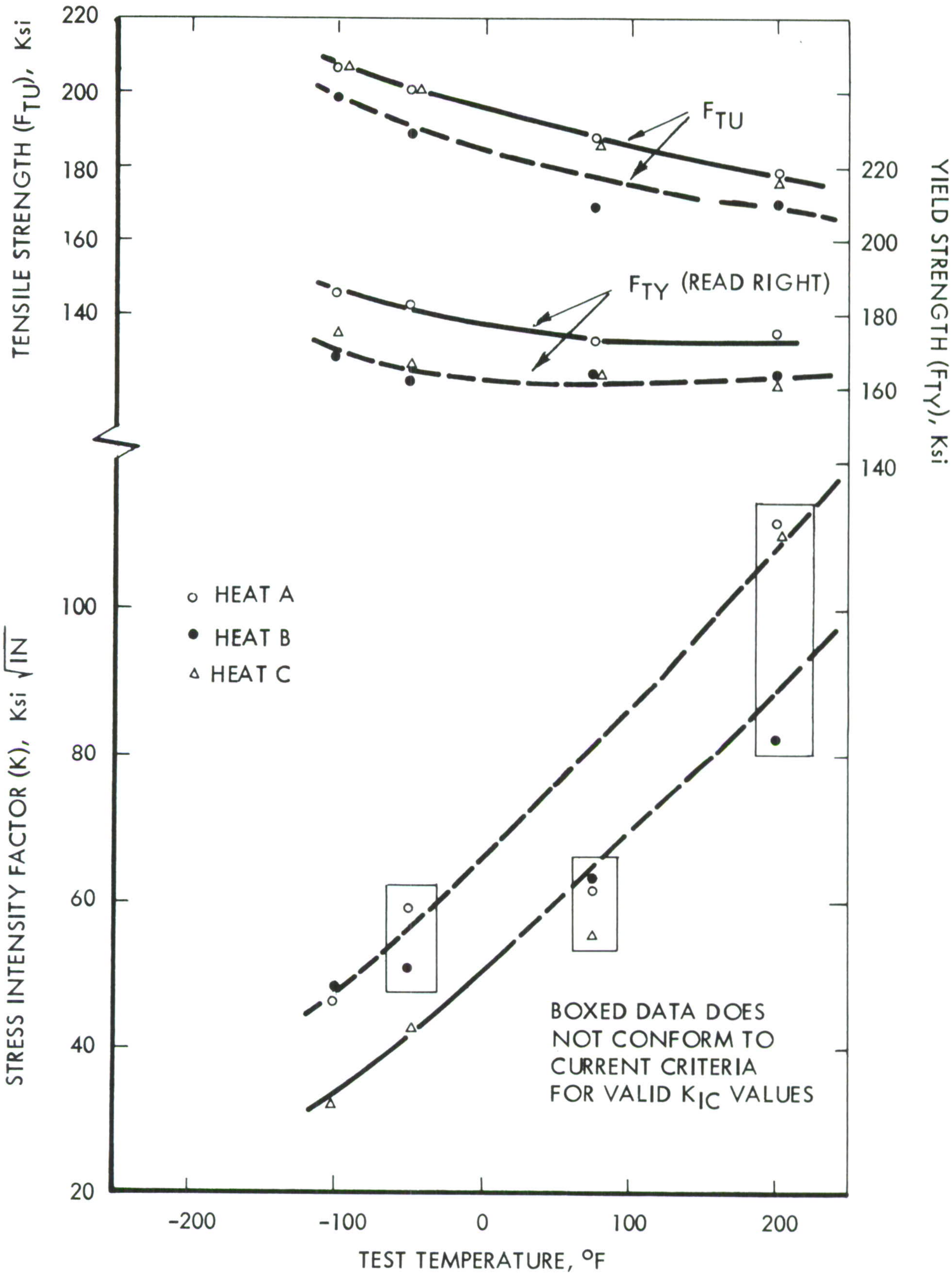


FIGURE 12 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 17-7 PH, CODE 8.

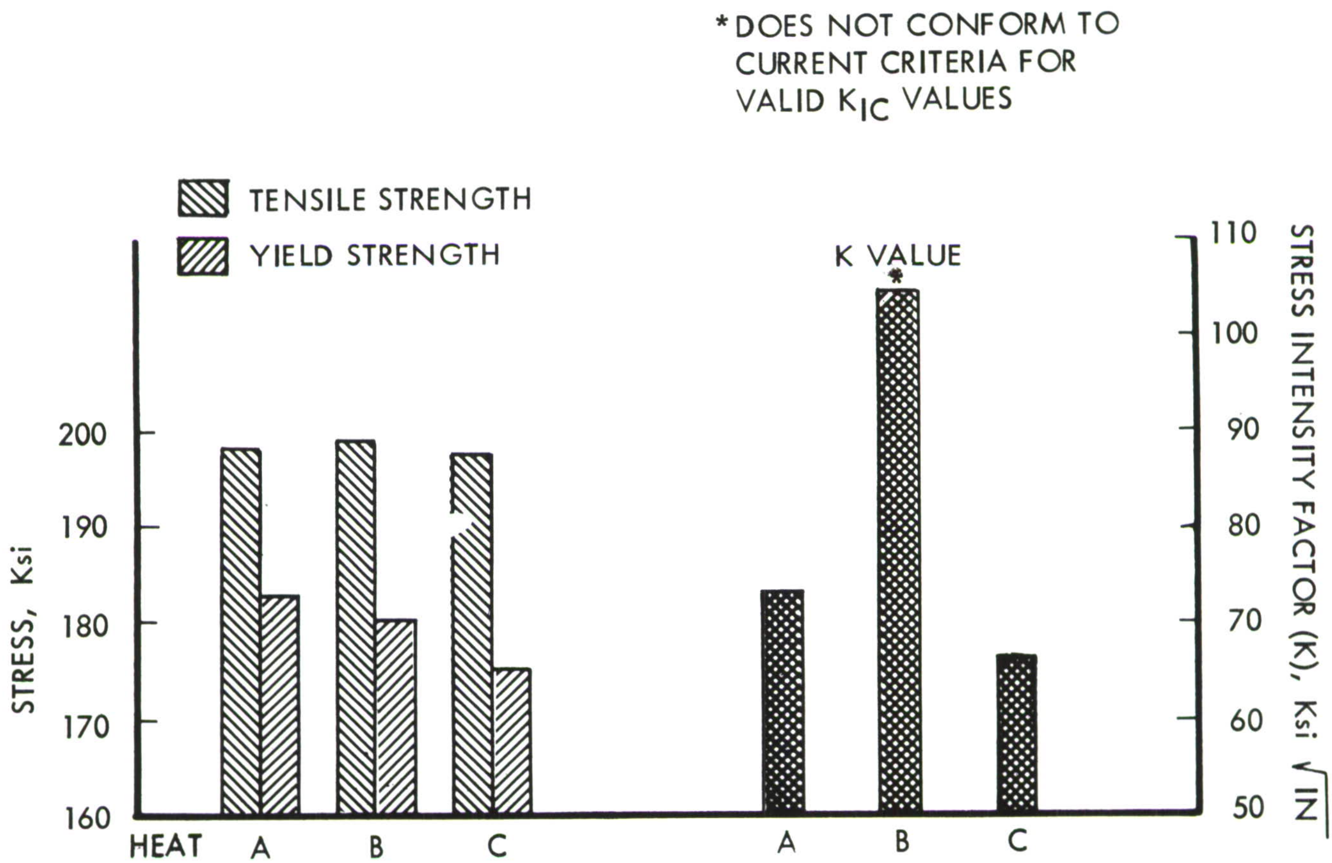


FIGURE 13 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 17-7 PH STEEL, CODE 9, ROOM TEMPERATURE TESTS.

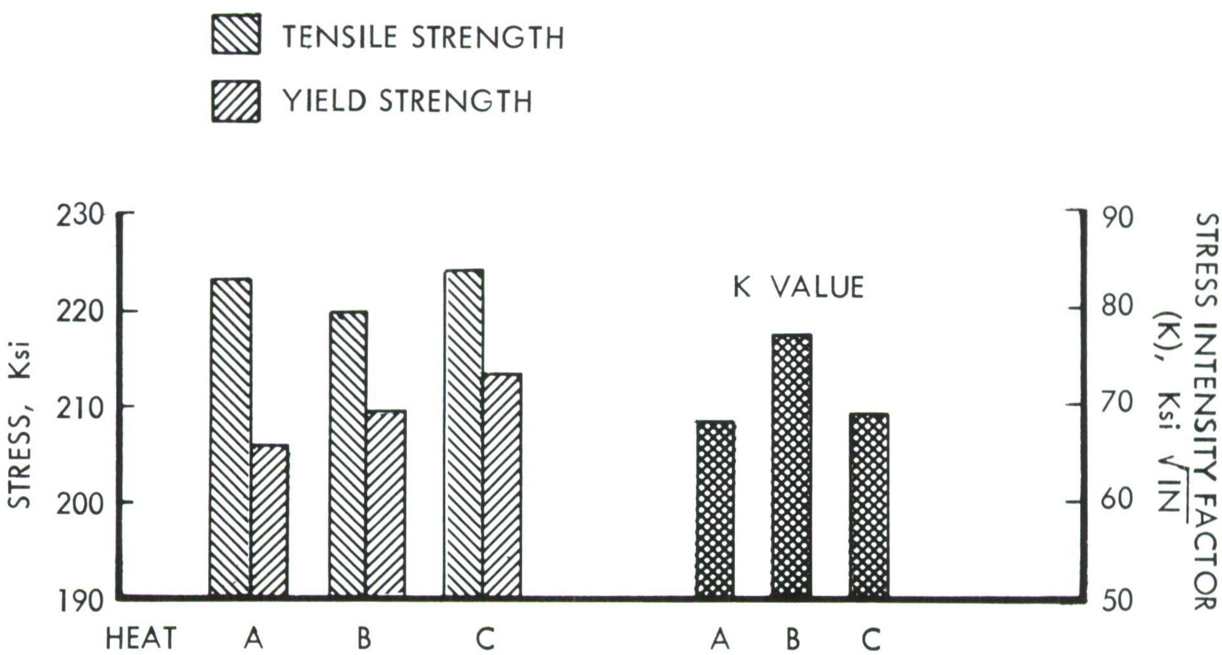
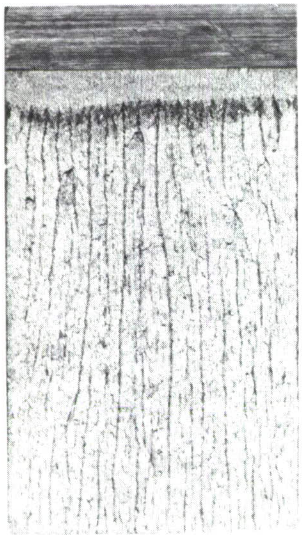
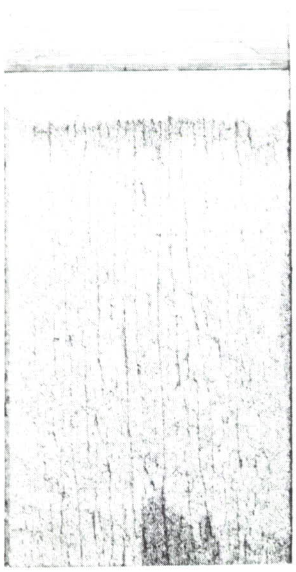


FIGURE 14 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 17-7 PH STEEL, CODE 10, ROOM TEMPERATURE TESTS.

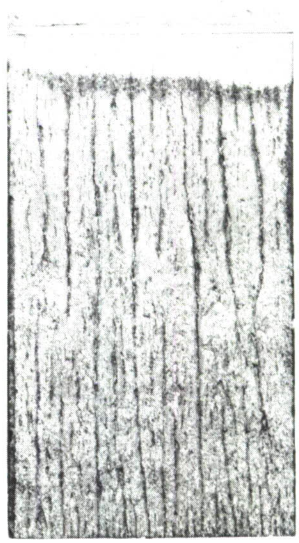


CODE 9, HEAT A

CODE 9, HEAT B



CODE 7, HEAT C



CODE 7, HEAT C

FIGURE 15 TYPICAL EXAMPLES OF DELAMINATIONS IN FRACTURE SURFACE OF 17-7 PH STEELS TESTED AT ROOM TEMPERATURE, 1.5X

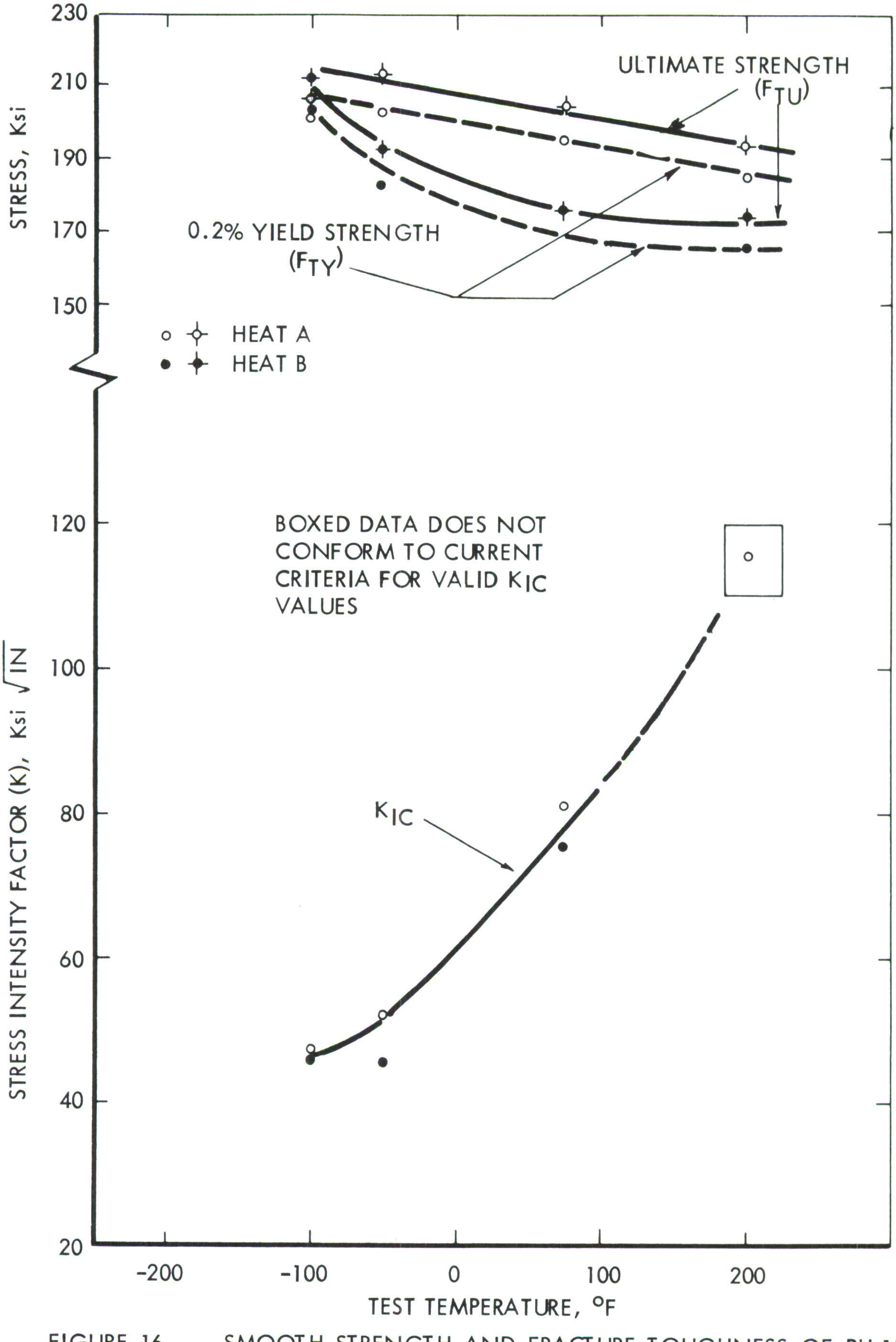


FIGURE 16 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF PH 15-7 Mo STEEL, CODE 11, TH 1050.

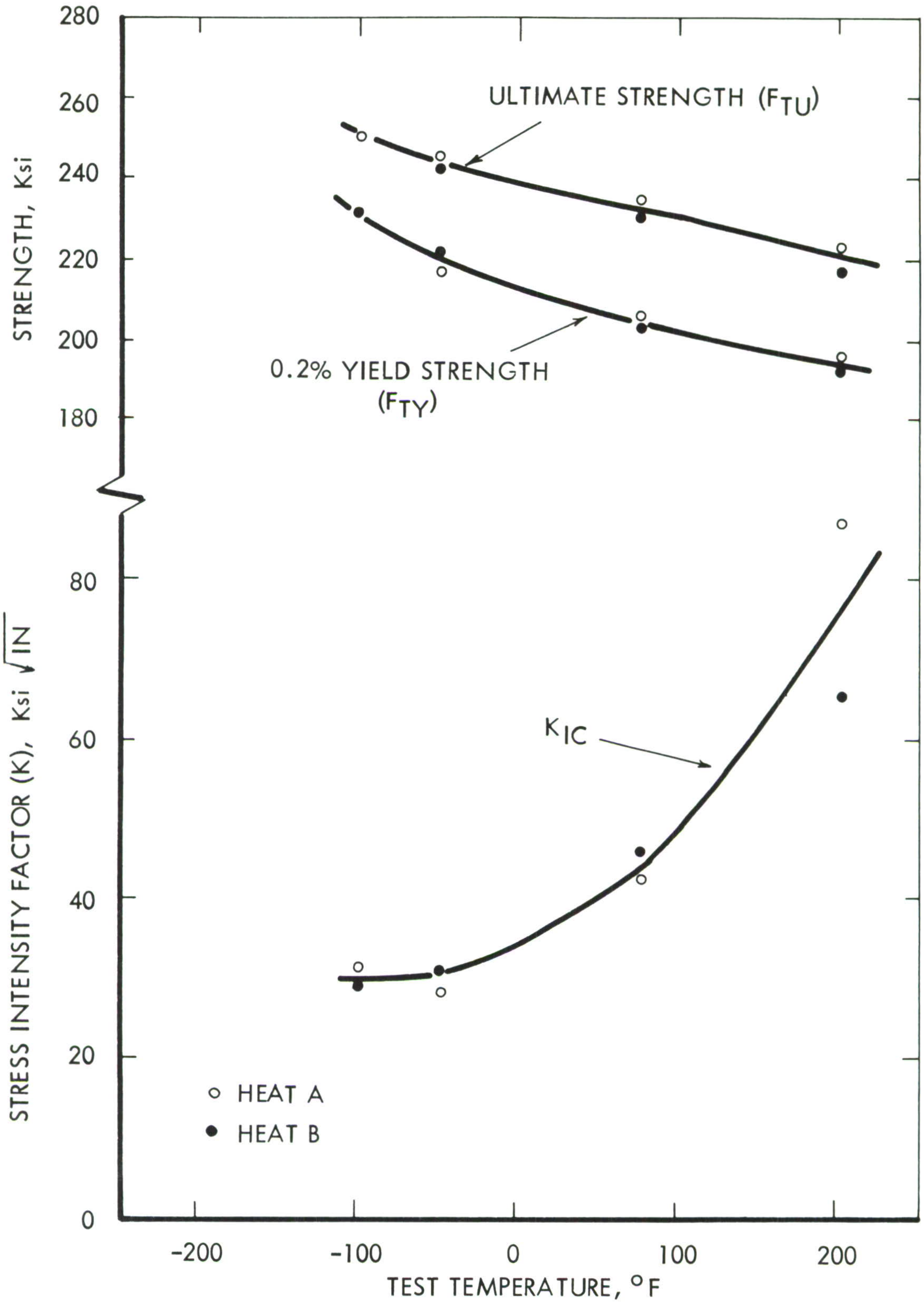
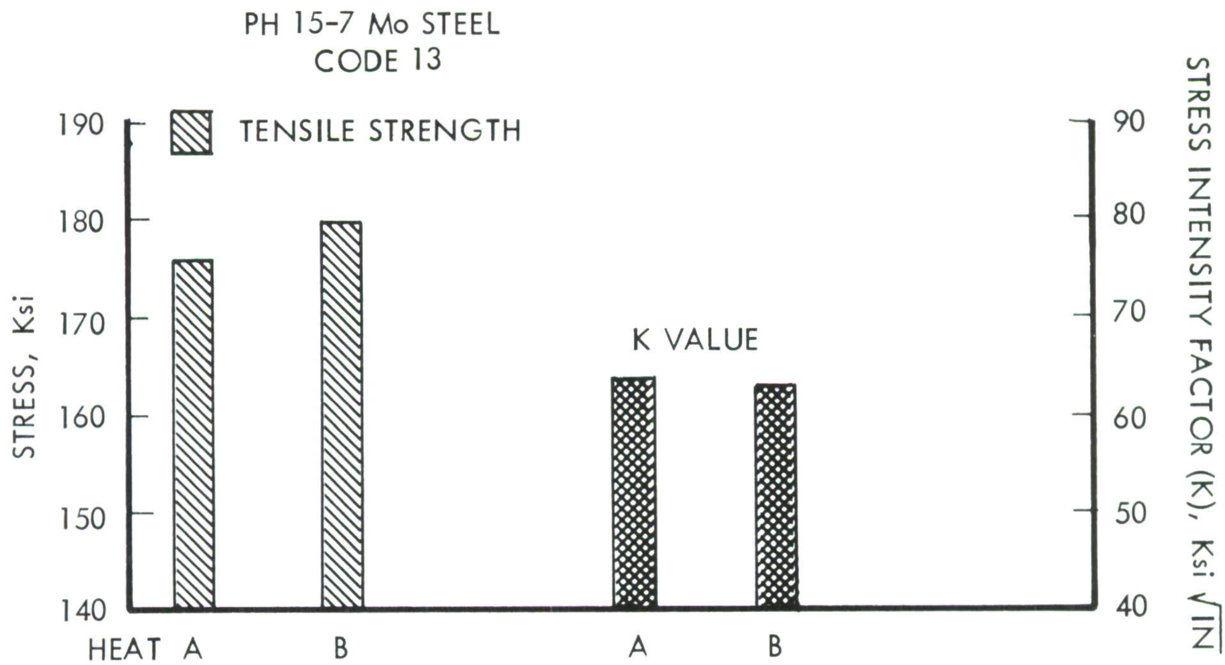


FIGURE 17 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF PH 15-7 Mo STEEL, CODE 12.



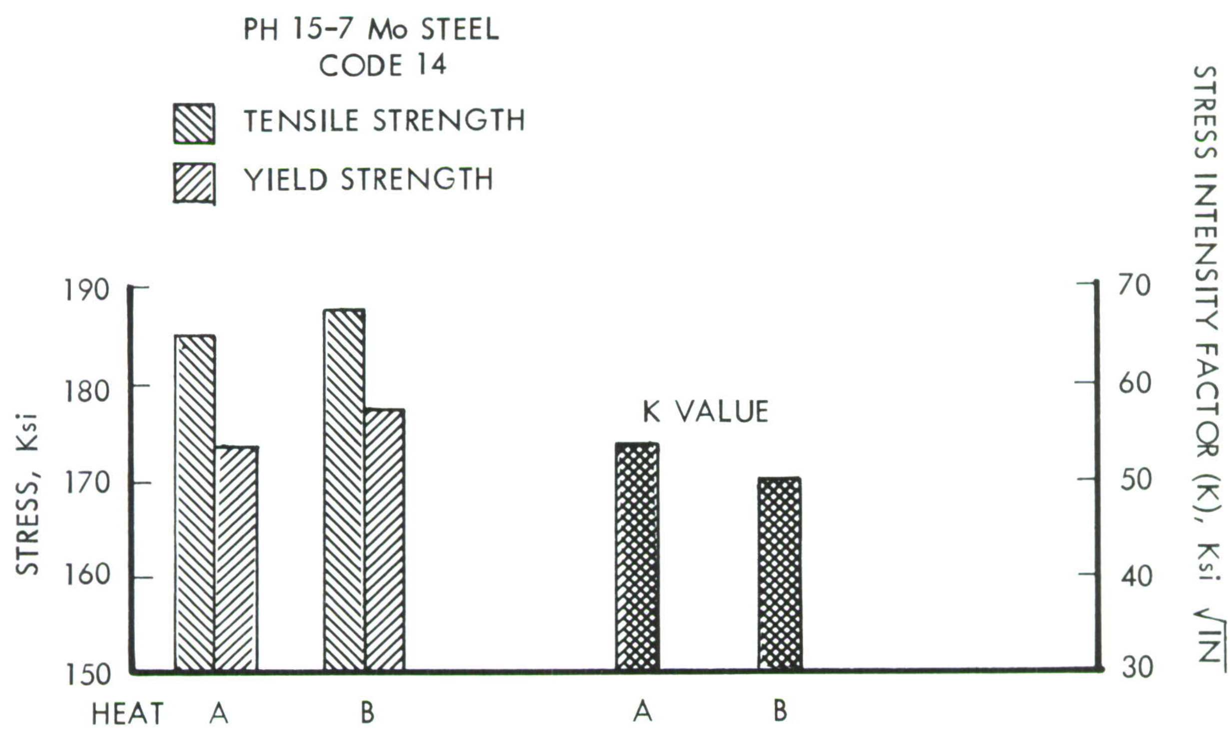


FIGURE 18 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF PH 15-7 Mo STEEL, CODES 13 AND 14, ROOM TEMPERATURE TESTS.

722 B

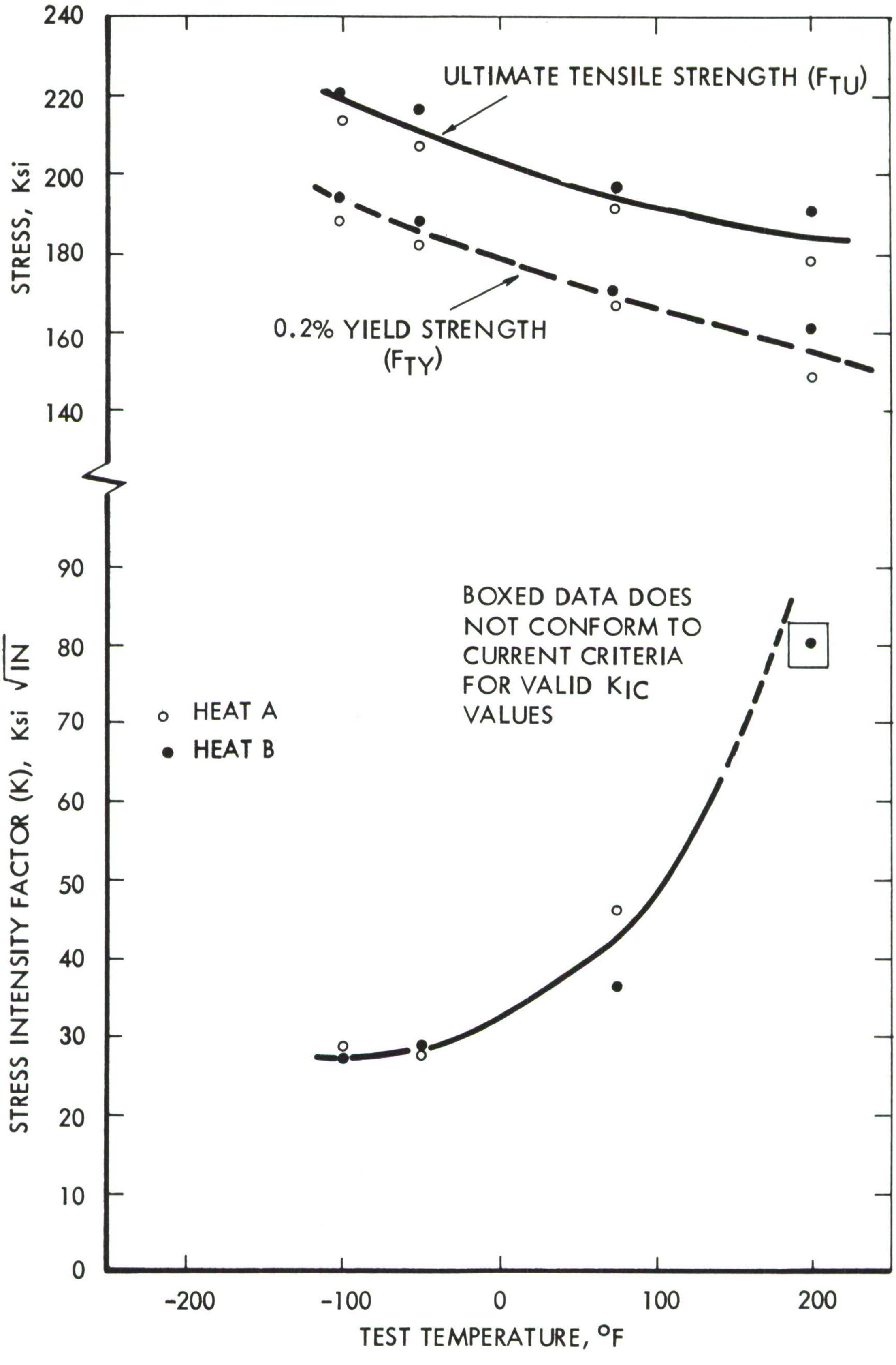


FIGURE 19 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF 17-4PH STEEL, CODE 15.

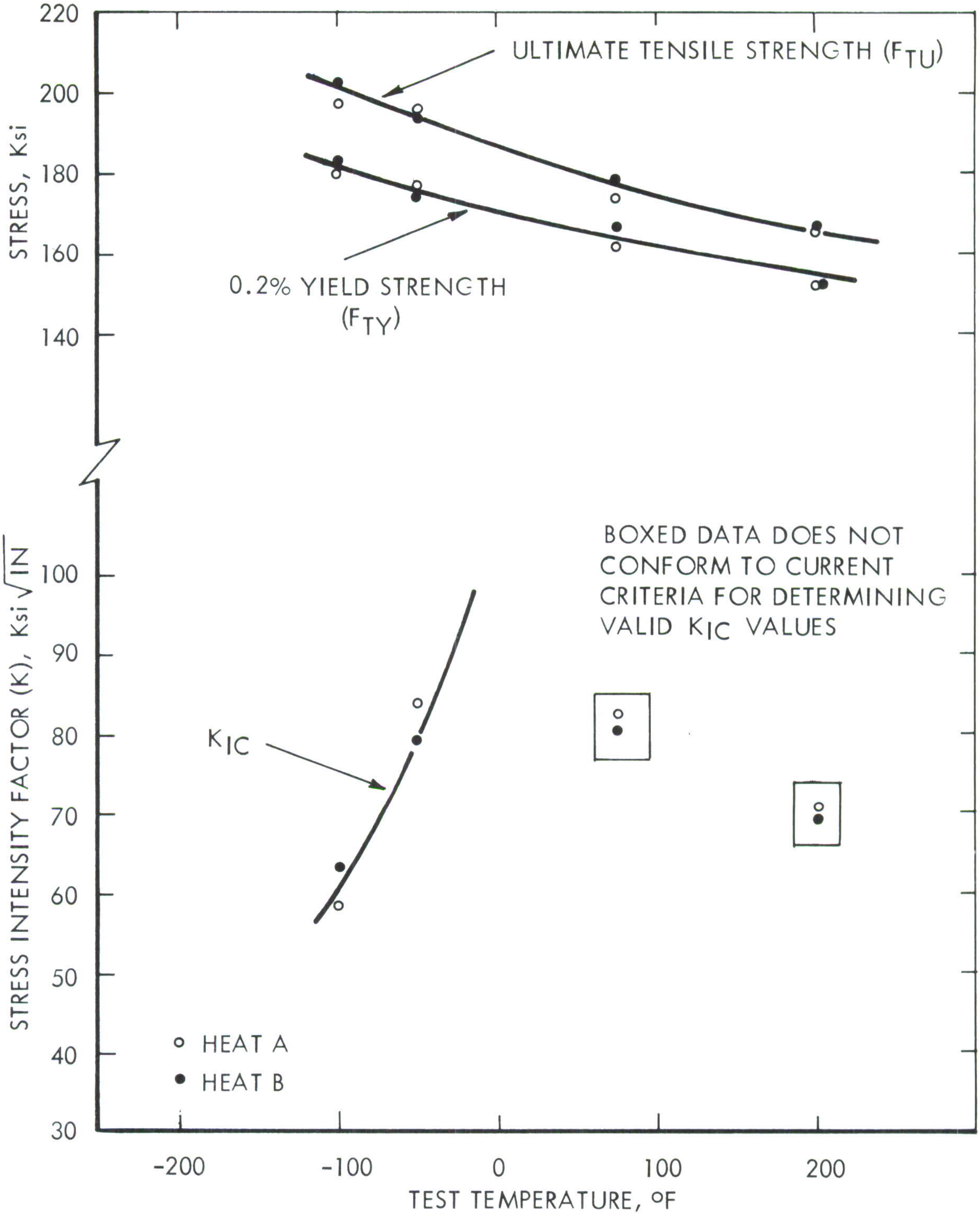


FIGURE 20 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF AM355 STEEL, CODE 17.

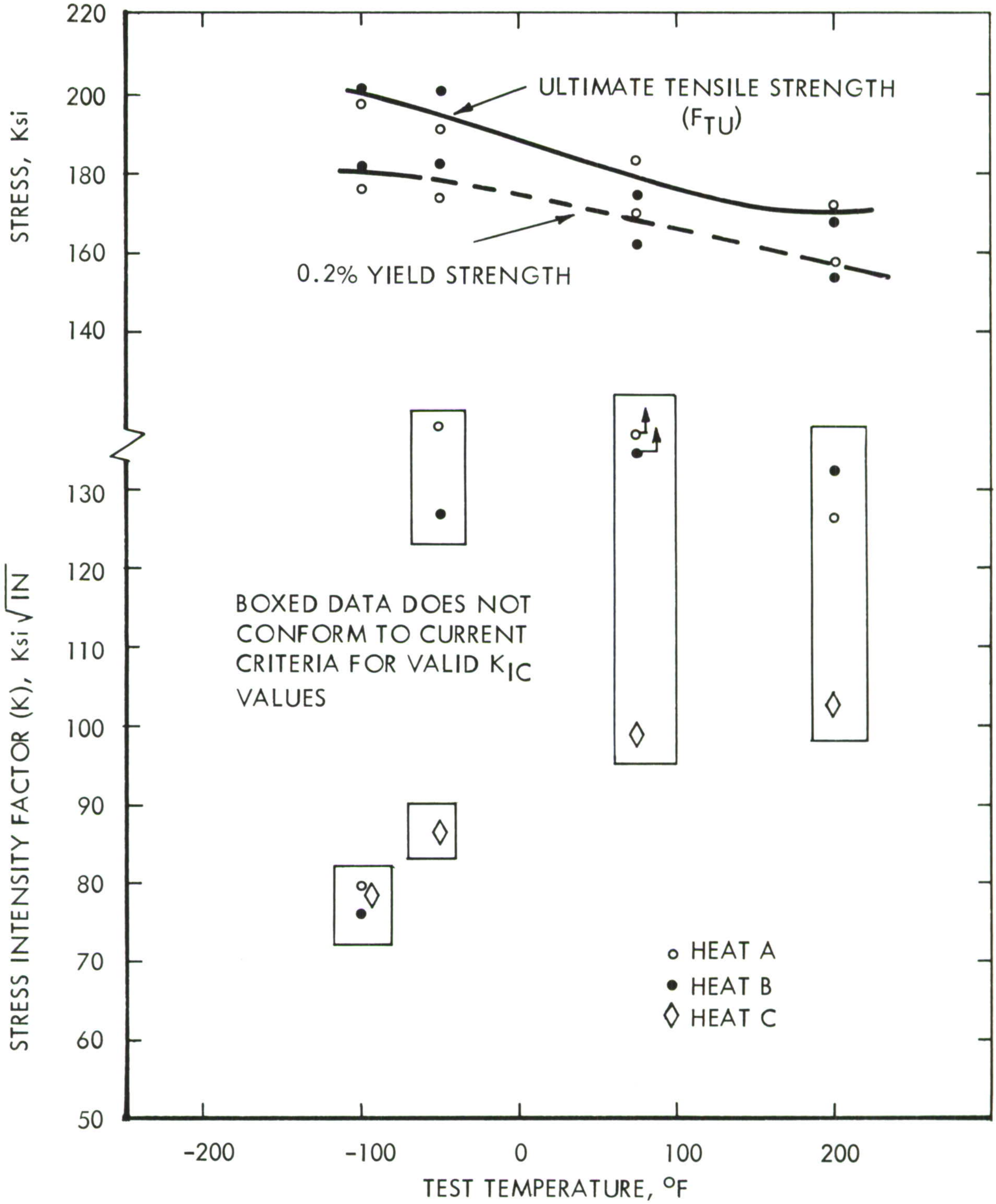


FIGURE 21 SMOOTH STRENGTH AND FRACTURE TOUGHNESS OF AM355 STEEL, CODE 19.

732 B

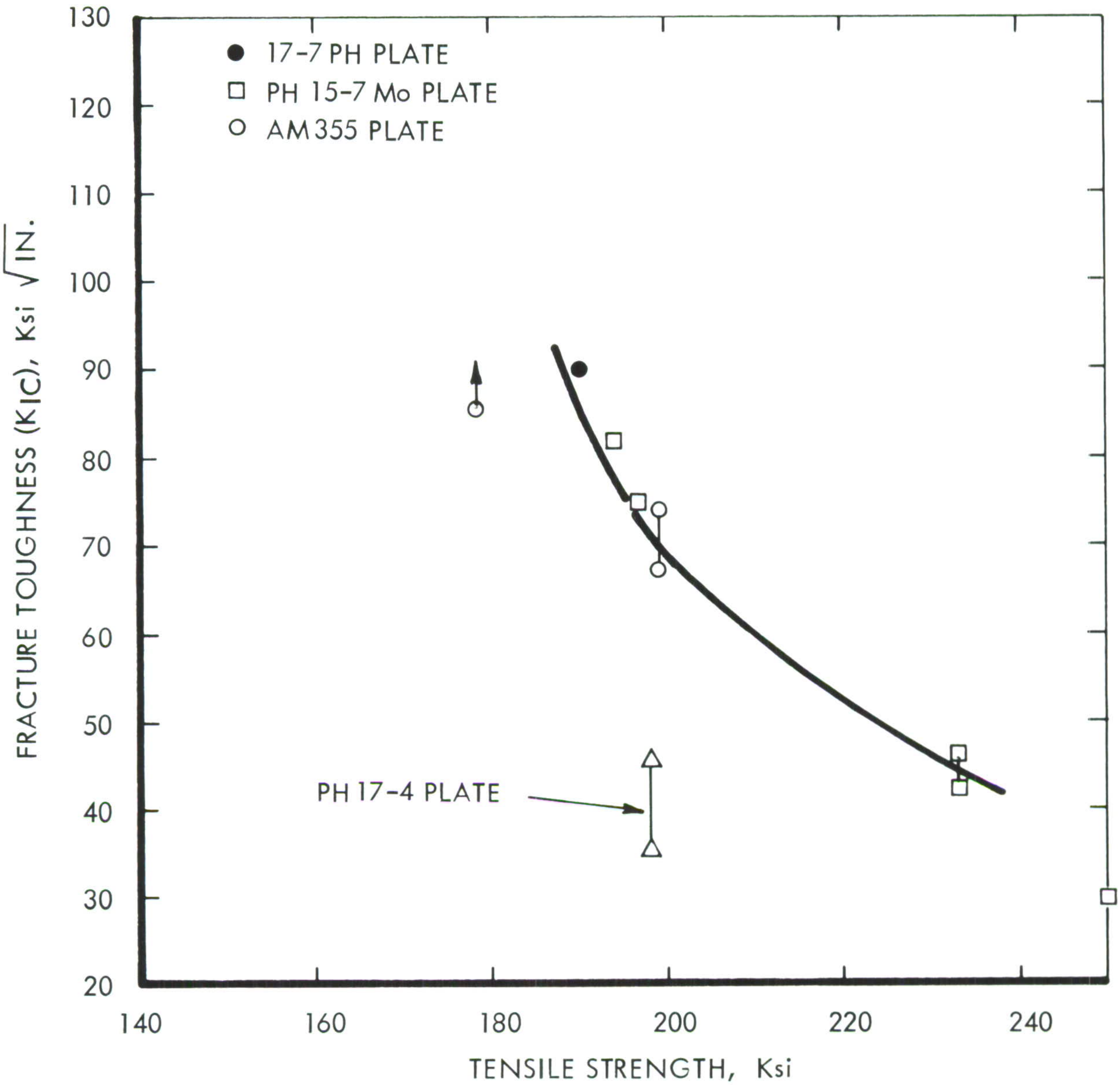


FIGURE 22 VARIATION IN ROOM TEMPERATURE FRACTURE TOUGHNESS WITH STRENGTH LEVEL FOR PRECIPITATION - HARDENING STAINLESS STEELS IN PLATE FORM.

708 B

4. Titanium Alloy (Ti-6Al-4V)

The variation of smooth strength properties and fracture toughness of three heats of the Ti-6Al-4V alloy as a function of test temperature is given in Figure 23. The data were considered as representing valid K_{IC} values at all test temperatures. An interesting feature was the relative insensitivity of K_{IC} to variations in test temperature from +75 to -100°F.

5. Applicability of Data to Handbook Presentation

The presentation of data in a design handbook, such as MIL Handbook 5 is done in one of two ways. The first method uses statistical techniques to list the limits in design properties, such as tensile strength, yield strength, bearing strength, etc. The second method used for fatigue properties and temperature effects involves the presentation of typical data in the form of representative property curves. Due to the relatively small quantity of data available and the variance between heats, the K_{IC} fracture toughness parameter lends itself more readily to the second method of presentation which involves giving typical data in graphical form.

The fracture toughness values generated in the current program were supplemented with data available in the literature which was considered valid. The criteria that were used to determine the acceptance of the additional data are presented in the Appendix. The data are summarized in Tables A38 through A40. The recent compilation developed by Wessel, Clark, and Wilson was primarily used to acquire the literature data (7).

The format selected involves presenting curves for each material. When sufficient data are available, the K_{IC} at room temperature is plotted as a function of tensile strength level. The second form of presentation gives the K_{IC} as a function of temperature. In this case, the fracture toughness is shown as a ratio of the K_{IC} at the specific test temperature to the K_{IC} at room temperature. The fracture toughness values presented in this manner are given in Figures 24 through 30 for the various classes of materials listed in MIL Handbook 5.

The data for the low alloy steels (Figure 24 consists mostly of results obtained with 4340 steel. A slight minimum in K_{IC} occurs in the strength region which corresponds to irreversible "500°F" temper embrittlement. Above a tensile strength of approximately 230 Ksi, the K_{IC} increases relatively rapidly. The variation in fracture toughness with temperature for the 4340 steel, heat treated to the 260 Ksi tensile strength level, is shown in Figure 25. Although the data are limited, this relationship appears to predict with reasonable accuracy the variation in K_{IC} which also occurs in the 4140 and 4340 alloy steels heat treated to lower strength levels.

The variation in K_{IC} as a function of strength level is shown in Figure 26 for the 5 Cr-Mo-V steels. The data obtained on sheet, bar and plate were combined since no definite difference appeared to exist as a function of material form. The variation in fracture toughness as a function of test temperature (shown in Figure 27) was comparable to that exhibited by the 4340 steel.

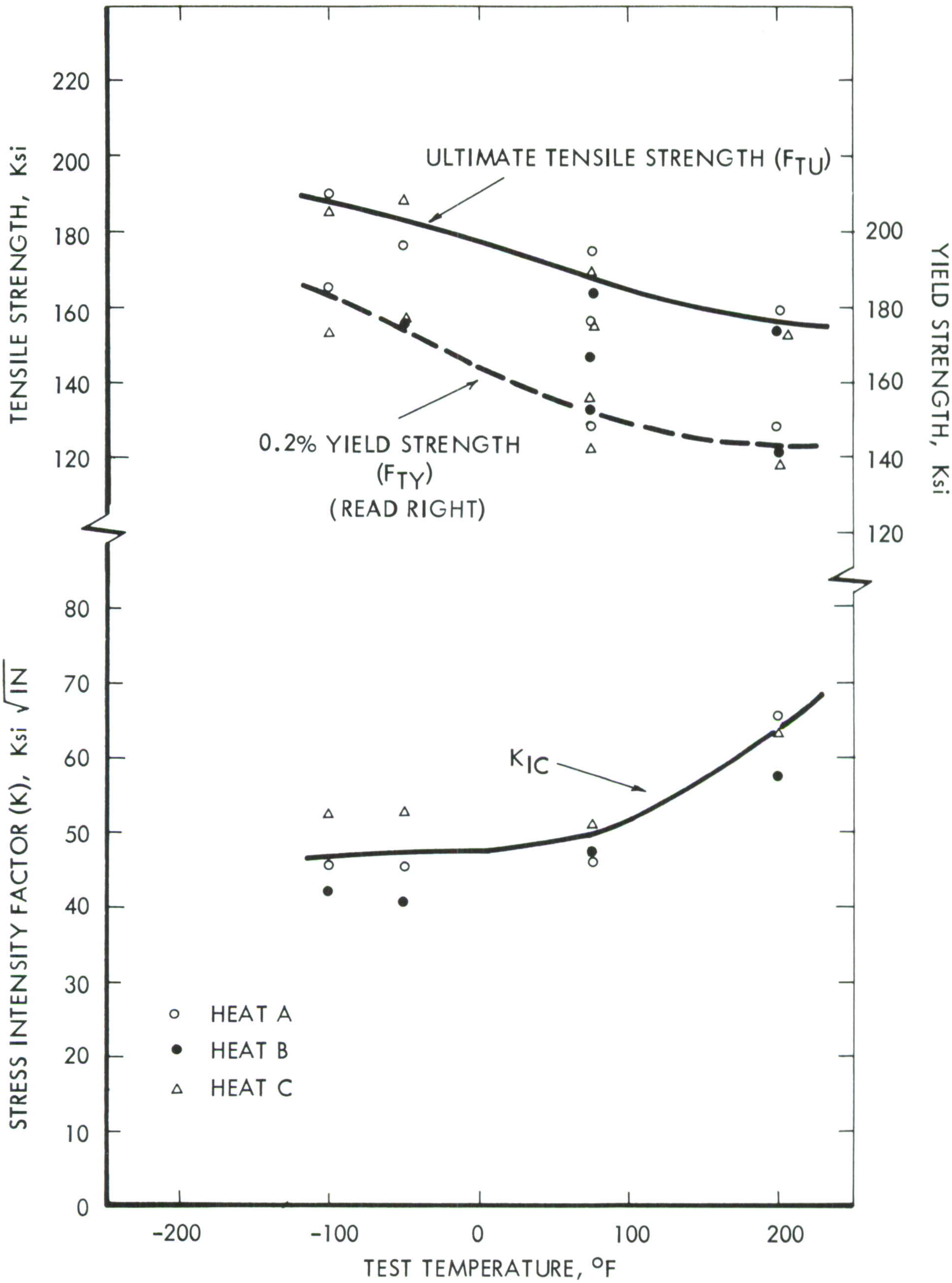


FIGURE 23 SMOOTH TENSILE AND FRACTURE TOUGHNESS OF 6Al-4V TITANIUM, CODE 20.

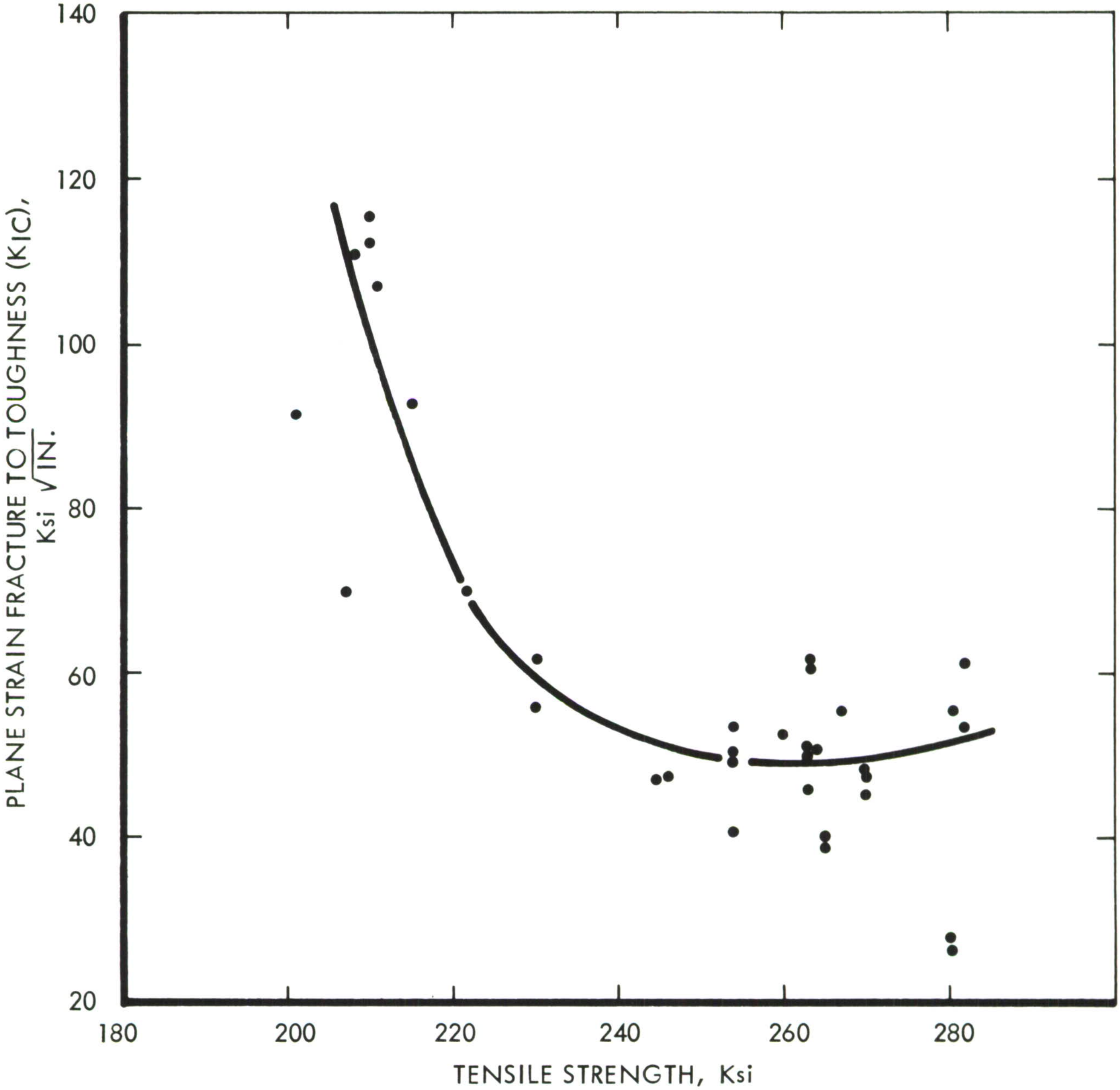


FIGURE 24 VARIATION OF K_{IC} WITH STRENGTH LEVEL, LOW ALLOY MARTENSITIC STEELS (4340, 4140), ROOM TEMPERATURE TESTS.

733 B

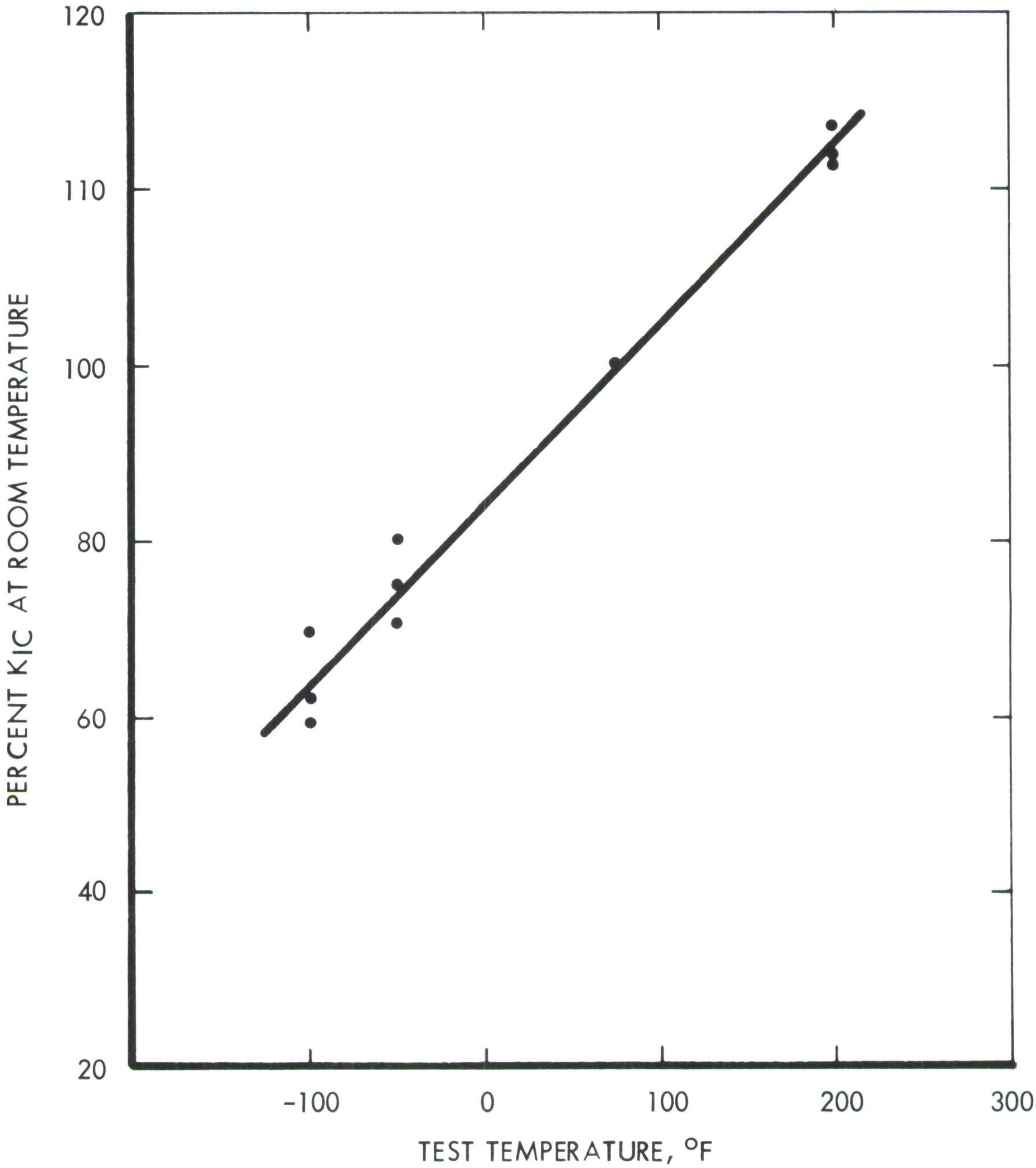


FIGURE 25 EFFECT OF TEMPERATURE ON THE PLANE STRAIN FRACTURE TOUGHNESS (K_{IC}) OF 4340 STEEL, 260 Ksi TENSILE STRENGTH AT ROOM TEMPERATURE.

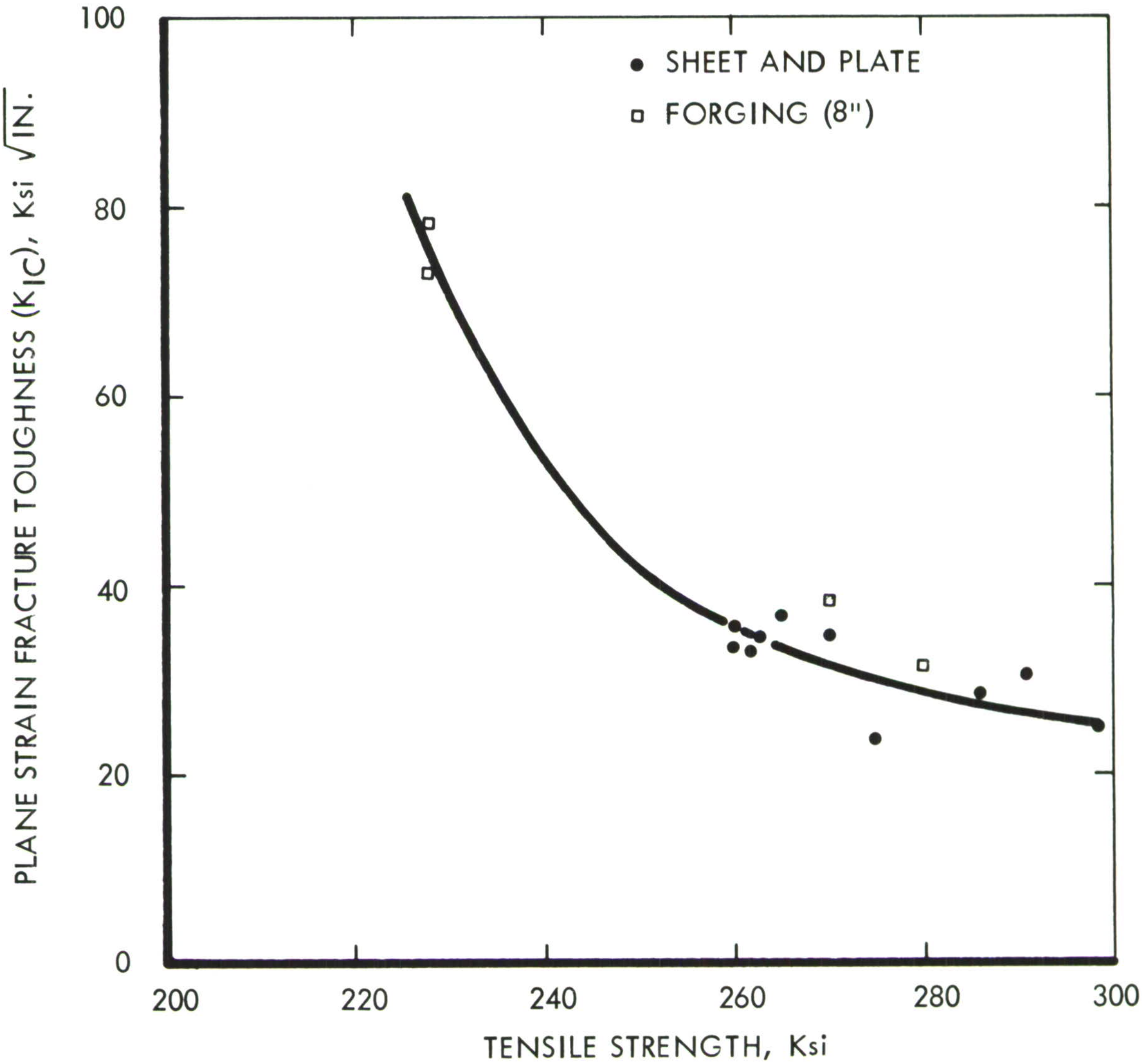


FIGURE 26 VARIATION OF K_{IC} WITH STRENGTH LEVEL, 5Cr-Mo-V STEEL, ROOM TEMPERATURE TESTS.

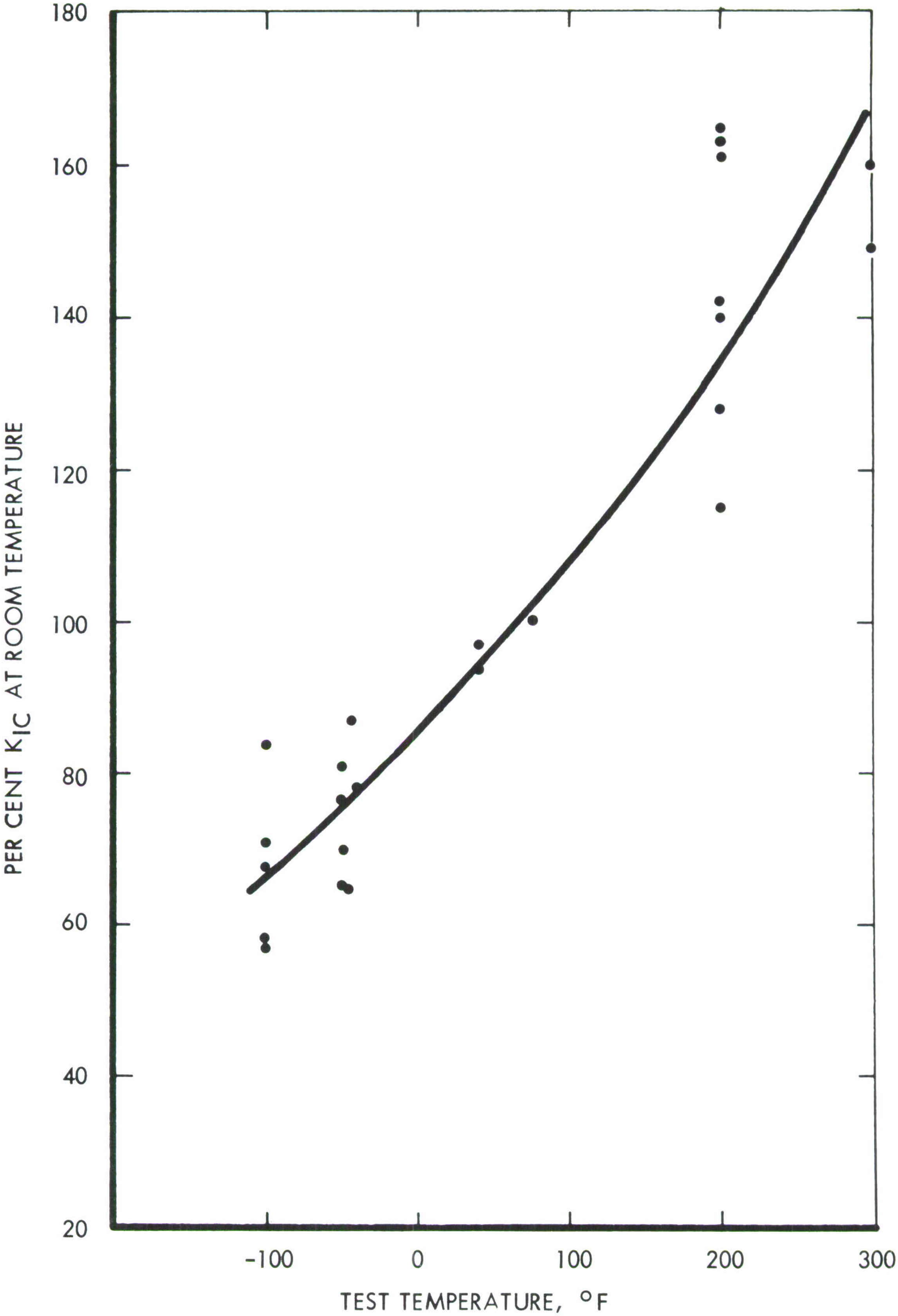


FIGURE 27 EFFECT OF TEMPERATURE ON THE PLANE STRAIN FRACTURE TOUGHNESS (K_{IC}) OF 5Cr-Mo-V STEEL.

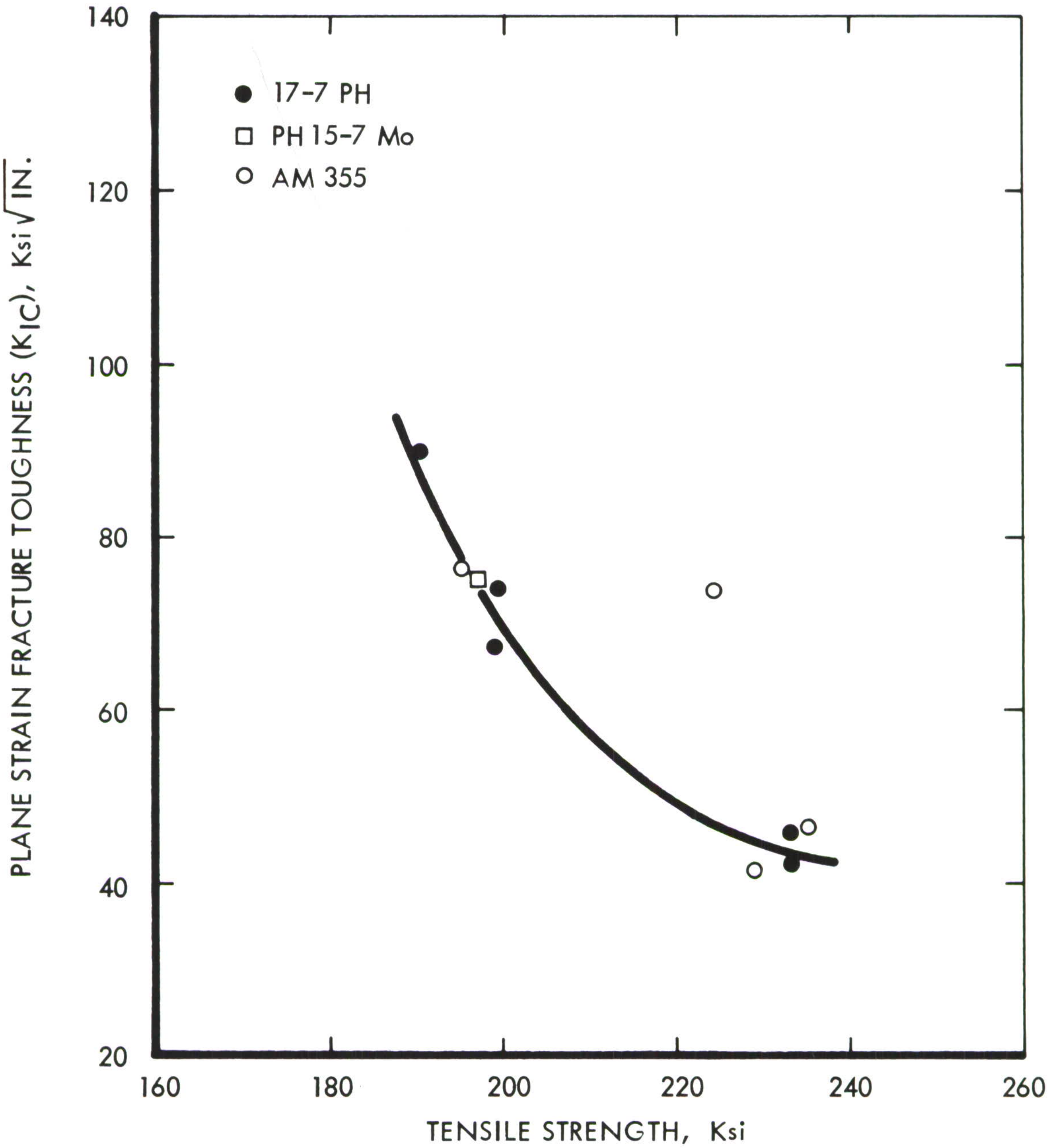


FIGURE 28 VARIATION IN ROOM TEMPERATURE FRACTURE TOUGHNESS WITH STRENGTH LEVEL FOR PRECIPITATION - HARDENING STEELS (17-7 PH, PH 15-7 Mo, AND AM355) IN PLATE FORM, ROOM TEMPERATURE TESTS.

709 B

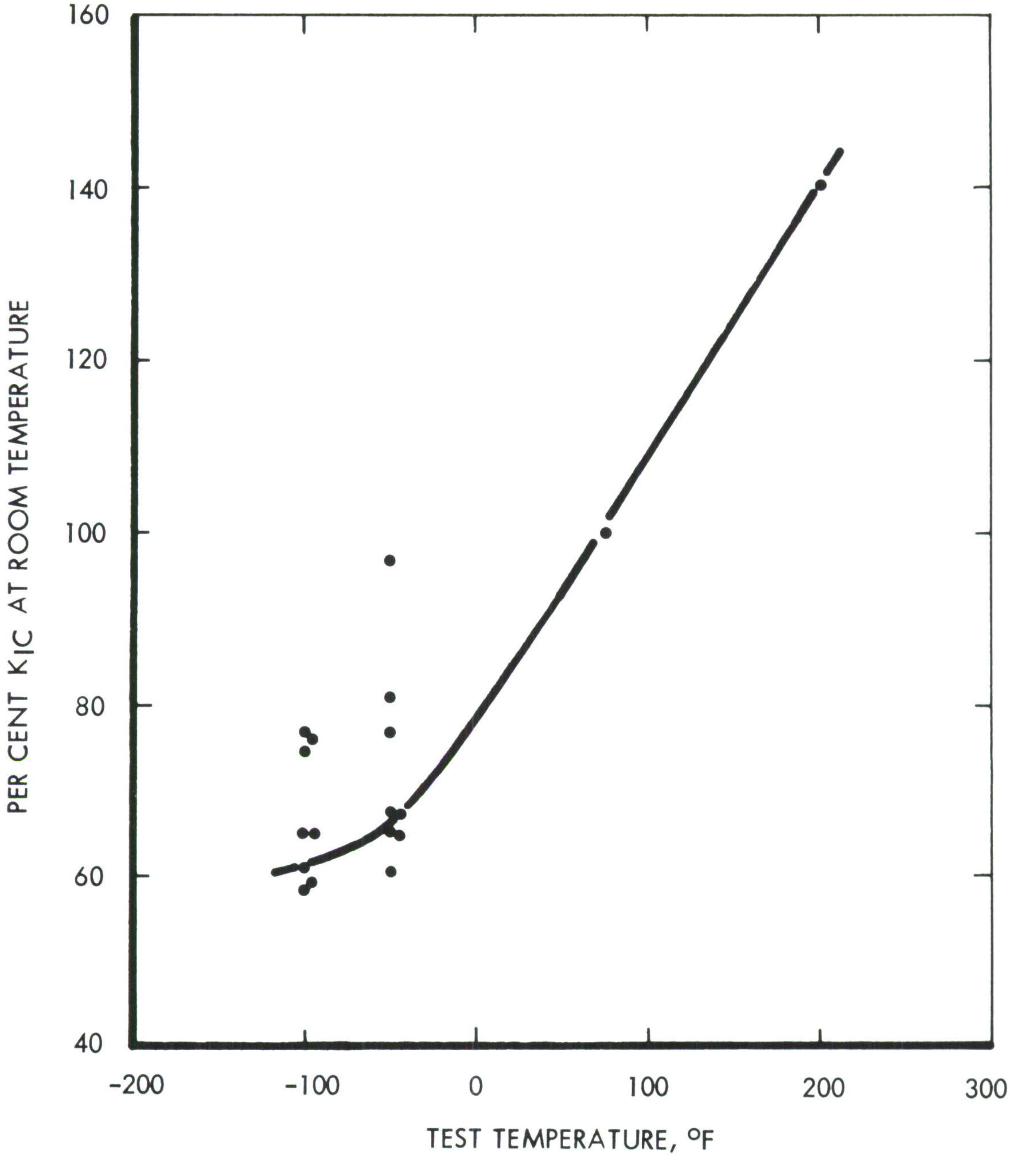


FIGURE 29 EFFECT OF TEMPERATURE ON THE PLANE STRAIN FRACTURE TOUGHNESS (K_{IC}) OF 17-7 PH, 15-7 Mo AND AM355 PRECIPITATION-HARDENING STAINLESS STEELS.

706 B

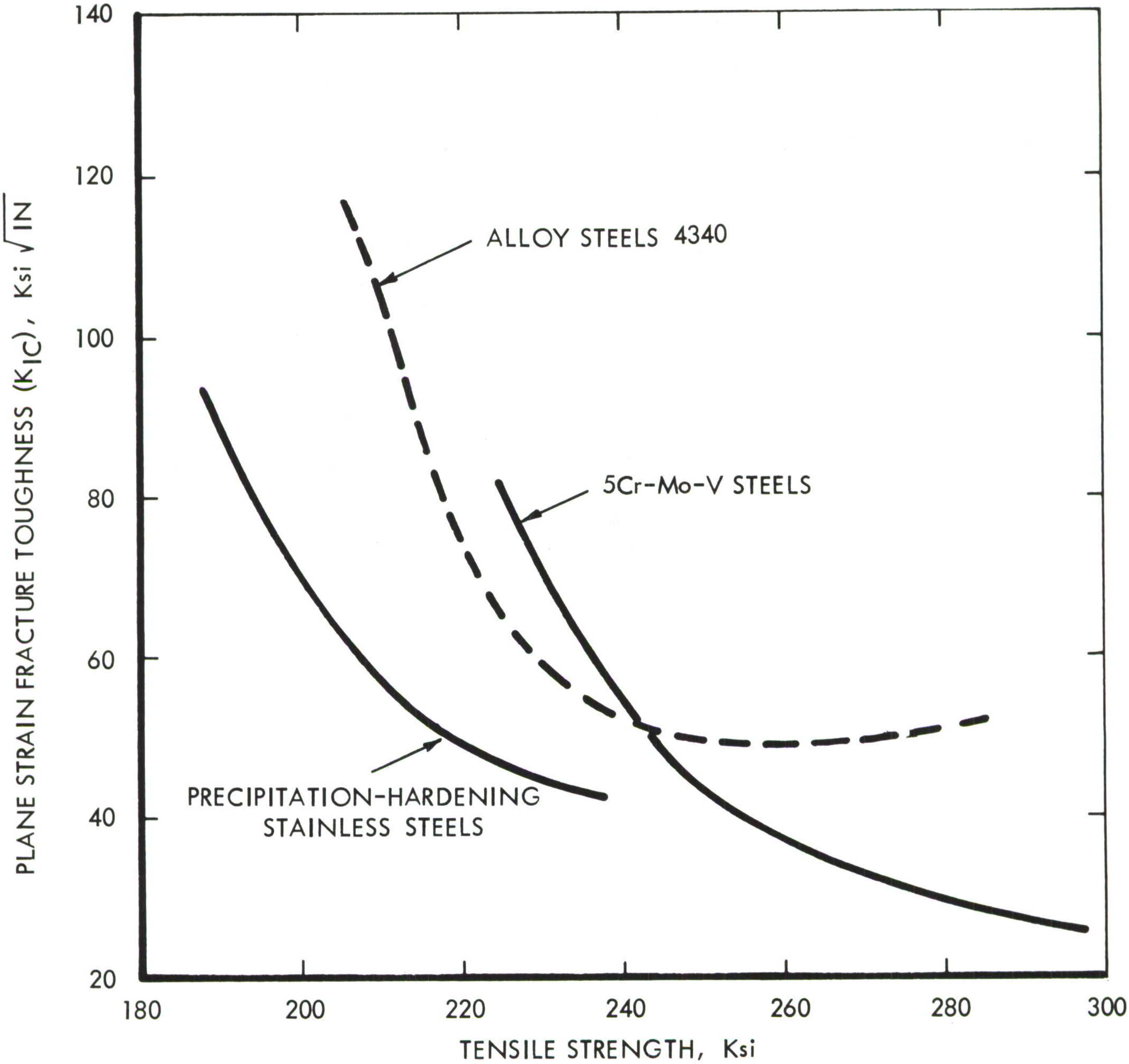


FIGURE 30 VARIATION OF FRACTURE TOUGHNESS WITH STRENGTH LEVEL FOR VARIOUS STEEL TYPES.

The variation of K_{IC} with strength level and temperature for the precipitation-hardening stainless steels are summarized in Figures 28 and 29. Relatively little data on these materials are available in the literature and the majority of results shown in these figures was produced by the current experimental program. In the -50 to +75°F range, the decrease in K_{IC} with decreasing temperature was greater for the precipitation-hardening stainless steels than for the 4340 or 5 Cr-Mo-V steels.

The comparison of the fracture toughness as a function of the various steel classes is shown in Figure 30. Above 240 Ksi, the 4340 steel type had a toughness which was significantly greater than the 5 Cr-Mo-V steels, however, at the lower strength levels, the two steels possessed comparable properties. The precipitation-hardening stainless steels had K_{IC} values below those of the other steels examined.

Although the results summarized in Figures 24 through 30 provide representative fracture toughness values which can aid in designing and selecting material conditions to preclude brittle fracture, the inherent variability in the K_{IC} value as a function of heat of material must receive adequate consideration. The scatter between heats can be as great as 30% and the material used for a specific design should be evaluated prior to use to insure that abnormally low fracture toughness do not exist.

SECTION IV

SUMMARY AND CONCLUSIONS

Tests were conducted using the precracked notch bend test to determine K_{IC} for a variety of high-strength materials. The ultimate goal of the program was to develop suitable fracture toughness values for presentation in handbook form. The materials evaluated included:

1) AISI Alloy Steels (4340 and 4140)
2) 5 Cr-Mo-V Steels,
3) Precipitation-Hardening Stainless Steels (17-7PH, 15-7Mo, 17-4PH, AM 355), and
4) Titanium Alloy (Ti-6Al-4V).

At least two heats of each material were tested over a range of strength levels and test temperatures between -100 and +200°F. The 4340 Alloy Steel showed good agreement between heats and slightly higher average K_{IC} values than 4140 steel. At the higher strength levels the 5 Cr-Mo-V steel had a fracture toughness less than 4340 steel however below approximately 240 Ksi tensile strength, the two materials showed comparable behavior. The 17-7PH, 15-7Mo, and AM 355 steels showed similar trends in K_{IC} as a function of strength level while the 17-4PH had a significantly lower toughness.

An analysis of the low temperature data indicates that the decrease in K_{IC} that occurs with decreasing temperature cannot be accounted for solely on the basis of the increase in yield or tensile strength.

The data for the materials evaluated were combined with the limited K_{IC} data available in the literature to produce representative curves of K_{IC} as a function of both tensile strength level and test temperature. These curves which could be presented as typical data in handbook form, would aid in the selection of materials for reliable component performance.

REFERENCES

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APPENDIX

Criteria Used to Select Valid K_{IC} Data

1. Notch Bend Test (3 or 4-point loading)

   $B \geq 2.5\ (K/F_{TY})^2$

   Major Span $>$ 4W

   $a \geq (K/F_{TY})^2$

2. Single-Edge-Notch Test

   $B \geq 2.5\ (K/F_{TY})^2$

   $a \geq (K/F_{TY})^2$

   Distance between loading pin holes $>$ 3W

3. Center-cracked Plate Specimens

   $B \geq 2.5\ (K/F_{TY})^2$

   $a \geq (K/F_{TY})^2$

   Distance between loading pin holes $>$ 4W

4. Notched Round Bar

   $D \geq 4.4\ (K/F_{TY})^2$

   $d = 0.707D$

   Length = 10D

CODE: B = specimen thickness; W = specimen width; a = crack size; K = fracture toughness; F_{TY} = 0.2% yield strength; D = major specimen diameter, d = minor specimen diameter.

TABLE A-1

FRACTURE TOUGHNESS DATA, 4340 STEEL, CODE 1, 265 KSI TENSILE STRENGTH, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
1A2-1	200	.391	.983	.395	III	2,340	62.2		.62			
1A2-2	"	.394	.975	.398	I	2,240	60.7		.62			
1A2-3	"	.388	.983	.314	III	2,640	56.9	59.9	.55	.083	4.7	4.4
1B2-1	"	.377	.987	.304	III	2,580	55.2		.54			
1B2-2	"	.377	.987	.347	III	2,435	58.4		.58			
1B2-3	"	.377	.987	.205	III	3,570	58.3	57.3	.56	.078	4.8	3.7
1C2-1	"	.376	.997	.355	I	2,625	63.0		.51			
1C2-2	"	.369	.996	.400	I	2,585	70.2		.69			
1C2-3	"	.376	.996	.211	I	3,885	63.6	65.6	.60	.099	3.8	3.3
1A7-1	75	.393	.975	.445	III	1,750	53.5		.55			
1A7-2	"	.392	.976	.448	III	1,735	53.5		.55			
1A7-3	"	.395	.959	.339	III	2,125	50.9	52.6	.48	.059	6.7	5.7
1B7-1	"	.376	.987	.327	III	2,200	50.0		.46			
1B7-2	"	.377	.987	.359	III	1,975	48.8		.46			
1B7-3	"	.375	.987	.207	III	3,200	52.7	50.5	.48	.054	6.9	3.8
1B7t-1	"	.377	.986	.391	-	2,000	53.9		.50			
1B7t-2	"	.377	.9 87	.366	III	2,075	52.2		.48			
1B7t-3	"	.377	.987	.210	III	3,185	52.6	52.9	.47	.056	6.7	3.7
1C7-1	"	.376	.997	.390	III	2,300	62.7		.57			
1C7-2	"	.376	.997	.435	III	2,075	51.4		.60			
1C7-3	"	.376	.996	.211	III	3,100	53.7	55.9	.45	.061	6.2	3.5
1A1-1	-100	.395	.995	.360	III	1,525	35.1		.30			
1A1-2	"	.393	.993	.440	III	1,395	40.0		.37			
1A1-3	"	.394	.985	.331	III	1,620	35.5	36.9	.31	.025	16.0	14.0
1B1-1	"	.376	.987	.310	III	1,490	32.3		.28			
1B1-2	"	.374	.987	.247	III	1,530	28.1		.24			
1B1-3	"	.376	.987	.201	III	2,115	33.9	31.4	.29	.018	21.0	14.1

TABLE A-1 (Cont'd)

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
1C1-1	-100	.369	.996	.293	III	1,480	30.6		.25			
1C1-2	"	.369	.996	.345	I	1,490	35.3		.30			
1C1-3	"	.368	.996	.202	III	2,065	33.3	33.1	.28	.019	19.4	14.7
1A5-1	-50	.396	.982	.375	-	1,740	43.1		.387			
1A5-2	"	.392	.904	.362	-	1,415	42.0		.399			
1A5-3	"	.390	.996	.348	III	1,820	41.2	42.1	.361	.033	11.1	11.0
1B5-1	"	.377	.987	.275	III	1,765	34.7		.297			
1B5-2	"	.376	.987	.348	III	1,630	39.1		.341			
1B5-3	"	.377	.987	.205	III	2,435	39.1	37.6	.340	.026	14.5	10.6
1C5-1	"	.374	.996	.326	III	1,870	41.7		.355			
1C5-2	"	.376	.997	.352	III	1,670	39.4		.340			
1C5-3	"	.376	.996	.205	III	2,395	38.2	39.8	.324	.029	13.1	10.1

TABLE A-2

SUMMARY OF SMOOTH TENSILE PROPERTIES, 4340 STEEL

Specimen	Test Temp.(°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
1A2	200	258.6	207.6	10.0	45.5
1B2	200	260.4	205.4	6.0	26.3
1C2	200	263.7	209.0	8.0	26.8
1A7	75	260.0	217.4	11.0	53.1
1B7	75	264.4	217.2	7.0	30.3
1C7	75	266.6	226.1	8.8	31.3
1B7T	75	266.2	223.3	11.0	47.7
1A5	-50	269.8	231.0	13.0	55.1
1B5	-50	272.7	233.2	8.0	29.9
1C5	-50	274.5	235.4	8.0	30.9
1A1	-100	276.0	235.4	10.0	50.7
1B1	-100	280.3	235.2	8.0	28.5
1C1	-100	279.7	240.0	9.0	30.4

TABLE A-3

FRACTURE TOUGHNESS DATA 4340 STEEL, CODE 2, 210 KSI TENSILE STRENGTH, FOUR-POINT LOADING, MAJOR SPAN = 5", MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
2A2-1	200	1.008	.992	.214	III	30,975	107.4		1.09			
2A2-2	"	1.007	.991	.220	III	29,447	103.7		1.06			
2A2-3	"	1.008	.993	.212	III	30,234	103.9	105.0	1.06	0.25	3.8	0.85
2B2-1	"	.999	.995	.197	III	34,401	114.4		1.16			
2B2-2	"	.999	.955	.233	III	29,308	107.0		1.08			
2B2-3	"	1.000	.995	.226	III	31,160	112.0	111.1	1.13	0.29	3.5	0.77
2C2-1	"	1.007	1.004	.231	II	32,410	115.3		1.18			
2C2-2	"	1.008	1.002	.219	II	33,336	115.2		1.18			
2C2-3	"	1.008	1.003	.254	III	29,771	112.8	114.4	1.15	0.30	3.3	0.78
2A7-1	75	1.010	.992	.196	III	29,586	107.6		1.03			
2A7-2	"	1.008	.992	.197	III	29,539	106.5		1.04			
2A7-3	"	1.010	.991	.200	III	29,586	108.1	107.4	1.05	0.23	4.2	0.85
2B7-1	"	.999	.995	.198	III	32,456	118.7		1.15			
2B7-2	"	.999	.995	.229	III	28,938	115.0		1.10			
2B7-3	"	.999	.994	.193	III	31,206	112.8	115.5	1.09	0.28	3.5	0.75
2C7-1	"	1.008	1.004	.227	II	28,891	110.7		1.07			
2C7-2	"	1.007	1.004	.218	II	30,141	113.2		1.09			
2C7-3	"	1.009	1.002	.216	II	30,465	114.2	112.7	1.10	0.27	3.8	0.85
2A5-1	-50	1.011	.991	.204	III	25,465	83.8		0.80			
2A5-2	"	1.008	.993	.192	III	26,808	85.3		0.81			
2A5-3	"	.990	.992	.199	III	26,437	87.6	85.6	0.83	0.15	6.8	1.3
2B5-1	"	.999	.996	.173	III	20,742	61.7		0.60			
2B5-2	"	.999	.995	.198	III	22,289	75.2		0.72			
2B5-3	"	.999	.995	.179	III	22,131	67.4	68.1	0.65	0.09	10.6	2.0
2C5-1	"	1.004	.999	.196	III	27,549	88.2		0.84			
2C5-2	"	.999	.995	.198	III	23,289	83.7		0.80			
2C5-3	"	.999	.995	.179	III	22,131	79.3	83.7	0.76	0.15	7.0	1.3

TABLE A-3 (Cont'd)

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
2A1-1	-100	1.008	.997	.194	III	21,511	67.5		0.63			
2A1-2	"	.996	1.007	.206	III	20,372	65.4		0.61			
2A1-3	"	1.003	.996	.208	III	19,446	64.0	65.6	0.60	0.09	12.2	2.4
2B1-1	"	.999	.995	.194	III	17,168	53.7		0.53			
2B1-2	"	.999	.995	.199	III	16,881	53.3		0.52			
2B1-3	"	.999	.995	.230	III	16,724	57.7	54.9	0.52	0.06	16.3	3.3
2C1-1	"	1.005	.990	.231	III	21,205	73.7		0.66			
2C1-2	"	1.008	.991	.243	III	21,150	75.6		0.65			
2C1-3	"	1.008	.994	.213	III	22,409	73.3	74.2	0.69	0.11	8.7	2.0

TABLE A-4

SUMMARY OF SMOOTH TENSILE PROPERTIES OF 4340 MATERIAL, CODE 2

Specimen	Test Temp.(^{o}F)	F_{TU} (Ksi)	F_{TY} (Ksi)	Elong. (1" G.L.)	% Red. in Area
2A2	200	205.0	187.7	11.0	50.4
2B2	200				
2C2	200	203.6	185.4	11.0	50.5
2A7	75	211.2	197.7	13.0	51.4
2B7	75				
2C7	75	210.9	197.4	12.0	50.9
2A5	-50	218.9	205.0	11.5	43.2
	-50				
2C5	-50	216.2	202.7	13.0	47.8
2A1	-100	224.9	210.9	11.0	46.5
2B1	-100				
2C1	-100	220.7	206.1	10.0	31.3

TABLE A-5

FRACTURE TOUGHNESS DATA 4140 STEEL, CODE 3, 205 KSI TENSILE STRENGTH, FOUR-POINT LOADING, MAJOR SPAN = 5", MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n/σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
3A2-1	200	1.021	1.002	.335	II	22,036	100.5		1.11			
3A2-2	"	1.021	.981	.240	II	26,160	98.5		1.07			
3A2-3	"	1.018	.982	.241	II	26,252	98.5	99.1	1.08	0.32	3.3	0.9
3B2-2	"	1.012	1.001	.244	II	33,660	126.0		1.29			
3B2-3	"	1.006	1.001	.578	I	19,446	165.9	146.0	2.41	0.63	1.5	0.6
3C2-1	"	1.026	1.000	.242	III	18,057	63.5		0.71			
3C2-2	"	1.024	.999	.574	III	12,445	98.6		1.57			
3C2-3	"	1.025	1.000	.321	III	15,399	66.5	76.2	0.76	0.21	4.9	1.9
3A7-2*	75	0.998	1.019	.240	III	21,715	92.6		0.93			
3A7-3**	"	1.00	1.015	.249	III	21,298	90.8	91.7	0.93	0.21	4.8	1.2
3A7T-1*	"	1.018	1.000	.311	II	14,075	70.9		0.75			
3A7T-2	"	1.019	0.981	.240	II	15,649	67.1		0.71			
3A7T-3*	"	1.017	0.981	.300	II	13,677	70.7	69.6	0.73	0.12	8.3	2.3
3B7-1*	"	1.019	0.999	.254	II	26,854	122.3		1.22			
3B7-2*	"	1.009	1.001	.245	II	25,650	114.0		1.14			
3B7-3*	"	1.011	0.998	.356	II	15,742	95.8+	110.7	0.97	0.26	3.8	1.1
3C7-2**	"	1.028	1.000	.225	III	18,289	70.5		0.73			
3C7-3**	"	1.027	0.999	.224	III	18,881	72.4	71.5	0.73	0.12	8.3	1.9
3A5-1	-50	1.024	1.001	.235	III	17,427	65.4		0.65			
3A5-2	"	1.021	1.002	.329	III	13,621	65.3	65.4	0.65	0.11	9.6	2.7
3B5-1	"	1.012	1.001	.238	III	14,788	55.1		0.55			
3B5-2	"	1.013	.998	.241	III	18,140	70.7		0.70			
3B5-3	"	1.013	1.001	.234	III	19,020	72.6	66.1	0.71	0.11	9.7	2.3

+ Irregular crack front, values not used
* Major span = 6"; Minor span = 3"
** Major span = 5-3/4"; Minor span = 2-7/8"

TABLE A-5 (Cont'd)

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
3C5-1	-50	1.032	1.001	.217	III	14,205	50.2		0.50			
3C5-3	"	1.028	1.000	.240	III	13,390	50.5	50.3	0.50	0.07	15.1	3.5
3C1-1	-100	1.014	1.002	.231	III	15,668	58.5		0.55			
3C1-2	"	1.013	1.001	.251	III	11,631	45.7		0.43			
3C1-3	"	1.014	1.000	.242	III	7,325	28.1	44.1	0.26	0.05	29.1	7.2
3B1-1	"	1.029	1.001	.208	III	12,260	42.2		0.42			
3B1-2	"	1.013	.998	.241	III	18,140	70.7		0.44			
3B1-3	"	1.013	1.001	.234	III	19,020	72.2	61.7	0.55	0.09	13.9	2.2
3A1-1	"	1.022	1.000	.219	III	14,353	51.7		0.50			
3A1-2	"	1.020	1.000	.315	III	10,918	50.6		0.49			
3A1-3	"	1.023	1.002	.236	III	14,640	55.0	52.4	0.53	0.06	16.4	4.2
3C5	-50	1.001	1.005	.175	III	22,965	67.6	67.6	0.67	0.12	8.6	1.5
3B1	-100	1.000	1.005	.171	III	16,798	47.8	47.8	0.48	0.05	18.6	3.3

TABLE A-6

SUMMARY OF SMOOTH TENSILE PROPERTIES, 4140 STEEL, CODE 3

Specimen	Test Temp.(°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
3A2	200	199.3	176.1	8.5	39.9
3B2	200	205.3	182.1	10.5	48.8
3C2	200	195.9	172.6	9.0	41.3
3A7	75	201.9	182.3	10.0	44.8
3B7	75	208.3	191.1	12.0	53.4
3C7	75	208.0	189.7	8.5	36.9
3A5	-50	219.5	199.8	9.5	35.6
3B5	-50	215.3	199.9	11.5	51.7
3C5	-50	216.8	198.7	8.5	34.6
3A1	-100	221.4	204.6	11.5	49.1
3B1	-100	225.5	208.7	12.0	47.8
3C1	-100	217.1	-	8.5	31.2

TABLE A-7

FRACTURE TOUGHNESS DATA, 5Cr-Mo-V STEEL, CODE 4, 260 KSI TENSILE STRENGTH, THREE-POINT LOAD, MAJOR SPAN=5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
4A2-1	200	.527	1.000	.225	III	3,970	47.5		.466			
4A2-2	"	.533	1.000	.229	III	4,370	52.4		.513			
4A2-3	"	.524	1.000	.093	III	9,040	71.1	57.0	.780	.080	6.6	2.3
4B2-1	"	.755	.755	.173	III	3,905	50.4		.522			
4B2-2	"	.755	.755	.157	III	4,235	51.5		.537			
4B2-3	"	.755	.755	.182	III	4,560	61.1	54.4	.629	.062	12.3	2.8
4A2-1	"	.538	1.001	.278	III	4,270	57.9		.560			
4A2-2	"	.541	.927	.294	III	3,275	55.0		.557			
4A2-3	"	.538	1.001	.201	III	5,200	57.1	56.7	.557	.078	6.9	3.3
4A7-1	75	.524	1.000	.263	III	2,625	34.9		.325			
4A7-2	"	.533	1.000	.260	III	2,760	35.8		.334			
4A7-3	"	.529	1.000	.163	III	3,640	36.1	35.6	.346	.028	18.8	8.2
4A7t-1	"	.525	1.000	.280	III	2,380	33.0		.308			
4A7t-2	"	.526	1.000	.252	III	2,335	29.9		.280			
4A7t-3	"	.525	1.000	.115	III	4,150	35.0	32.7	.356	.024	22.2	9.1
4B7-1	"	.755	.754	.219	III	2,505	38.0		.366			
4B7-3	"	.755	.755	.207	III	1,970	28.5	33.3	.274	.020	38.4	10.8
4A′7-1	"	.541	1.000	.291	III	2,505	34.7		.320			
4A′7-2	"	.536	1.000	.284	III	2,490	34.1		.315			
4A′7-3	"	.537	1.000	.213	III	3,030	34.3	34.4	.317	.025	21.2	10.3
4A′7t-1	"	.538	1.000	.294	III	2,230	31.3		.306			
4A′7t-2	"	.544	1.000	.245	III	2,250	27.4		.267			
4A′7t-3	"	.538	.990	.223	III	3,015	35.8	31.5	.350	.024	22.6	10.6
4A5-1	-50	.535	1.000	.257	III	1,610	20.6		.187			
4A5-2	"	.531	1.000	.216	III	1,820	20.9		.191			
4A5-3	"	.526	1.000	.147	III	2,955	28.0	23.2	.264	.011	20.5	18.8
4B5-1	"	.755	.756	.212	III	1,415	20.7		.199			
4B5-2	"	.755	.755	.188	III	1,425	19.2		.184			
4B5-3	"	.755	.755	.208	III	1,710	24.8	21.6	.237	.008	92.4	24.8

TABLE A-7 (Continued)

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
4A′5-1	-50	.542	.992	.279	III	1,580	21.6		.201			
4A′5-2	"	.540	.998	.296	III	1,565	22.2		.206			
4A′5-3	"	.540	.998	.181	III	2,705	27.9	23.9	.263	.013	43.2	20.1
4A1-1	-100	.525	1.000	.175	III	1,860	19.2		.169			
4A1-2	"	.526	1.000	.234	III	1,610	19.7		.169			
4A1-3	"	.588	1.000	.159	III	2,590	22.7	20.5	.202	.024	22.7	7.9
4B1-1	"	.755	.755	.198	III	1,330	18.6		.170			
4B1-3	"	.755	.755	.264	III	1,585	19.8	19.2	.260	.006	129.1	39.5
4A′1-2	"	.537	.999	.277	III	1,470	19.8		.175			
4A′1-3	"	.536	.999	.211	III	2,390	26.9	23.4	.239	.011	49.6	22.5

TABLE A-8

SUMMARY OF SMOOTH TENSILE PROPERTIES, 5Cr-Mo-V STEEL, CODE 4

Specimen	Test Temp. °F	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
4A2	200	247.7	201.7	12.0	47.4
4C2	200	247.6	203.4	10.0	34.2
4A7	75	260.4	212.6	12.0	51.9
4C7	75	262.7	215.8	12.0	52.0
4C7T	75	252.2	204.0	11.0	45.9
4A5	-50	264.0	219.1	12.5	50.5
4C5	-50	265.5	213.7	10.0	46.4
4A1	-100	278.5	231.1	12.0	46.6
4C1	-100	278.8	225.1	12.0	49.6

TABLE A-9

FRACTURE TOUGHNESS DATA, 5 Cr-Mo-V STEEL, CODE 5, 275 KSI TENSILE STRENGTH, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
5B2-2	200	1.001	1.003	.258	III	3,925	26.7	26.7	.23	.014	74.0	19.0
5B7-3	75	1.002	1.001	.221	III	3,780	23.3	23.3	.19	.014	73.3	16.1
5B5-1	-50	1.002	1.002	.276	III	2,420	17.3		.14			
5B5-2	"	1.002	1.002	.299	III	2,275	17.3		.14			
5B5-3	"	1.001	.998	.214	III	3,100	18.9	17.8	.15	.005	199.2	52.3
5B1-1	-100	1.003	1.002	.330	III	2,100	17.3		.13			
5B1-2	"	1.003	.997	.237	III	2,345	15.2		.12			
5B1-3	"	1.001	1.003	.214	III	2,855	17.2	16.6	.13	.004	249.4	64.7

TABLE A-10

FRACTURE TOUGHNESS DATA, 5Cr-Mo-V STEEL, CODE 6, 240 KSI TENSILE STRENGTH, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
6A2-1	200	1.030	.936	.232	III	9,100			Severe quench crack, data no used.			
6A2-2	"	1.030	1.000	.236	III	12,570	80.6		.792			
6A2-3	"	1.029	.999	.184	III	17,070	95.8	88.8	.946	.198	5.0	1.1
6A5-1	-50	1.031	1.000	.334	III	3,440	28.1		.268			
6A5-2	"	1.030	.982	.258	III	2,790			Severe quench crack, data not used			
6A1-1	-100	1.032	1.000	.278	III	3,315	23.2		.210	.015	66.6	18.5
6B5-3	-50	.752	.753	.127	III	2,295	25.0	25.0	.119	.014	53.0	9.1

TABLE A-11

SUMMARY OF SMOOTH TENSILE PROPERTIES, 5Cr-Mo-V STEEL, CODE 6

Specimen	Test Temp. (°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
6A2	200	236.4	198.0	13.0	61.1
6A7	75	239.4	199.4	13.5	50.1
6A5	-50	260.1	210.1	10.5	50.1
6A1	-100	267.8	219.8	12.0	52.5

TABLE A-12

FRACTURE TOUGHNESS DATA 17-7PH STEEL, CODE 7, FOUR-POINT LOADING, MAJOR SPAN = 5"; MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n/σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
7A2-1	200	.529	.993	.239	II	12,714	89.3		1.05	0.30	1.7	0.8
7A2-2	"	.534	.992	.306	II	10,705	88.9		1.05	0.29	1.7	1.0
7A2-3	"	.534	1.001	.241	II	12,334	84.4	87.5	0.99	0.27	2.1	0.9
7B2-1	"	.501	1.013	.190	I	20,002	128.6		1.45	0.63	0.8	0.3
7B2-2	"	.502	1.002	.189	II	16,399	105.6		1.23	0.43	1.2	0.4
7B2-3	"	.511	1.002	.209	I	18,835	128.3	120.8	1.45	0.63	0.8	0.3
7C2-1	"	.509	1.002	.193	I	18,131	116.7		1.37	0.56	0.9	0.3
7C2-2	"	.511	1.013	.205	II	16,612	108.2		1.27	0.47	1.1	0.4
7C2-3	"	.510	1.015	.217	II	15,890	106.5	110.5	1.25	0.45	1.1	0.5
7A7-1	75	.514	1.004	.245	III	9,621	67.7		0.80			
7A7-2	"	.514	1.004	.229	II	8,862	59.4		0.71			
7A7-3	"	.532	.992	.344	II	7,139	70.9	66.0	0.85	0.16	3.0	1.6
7A7T-1	"	.507	1.002	.183	III	12,316	83.2		1.03			
7A7T-3	"	.537	.999	.203	III	9,593	64.1	73.7	0.80	0.20	2.7	1.0
7B7-1	"	.501	1.002	.171	III	12,983	85.1		0.92			
7B7-2	"	.507	1.002	.180	II	14,233	95.2		1.02			
7B7-3	"	.502	.990	.212	II	11,047	82.9	87.7	0.89	0.23	2.2	0.8
7C7-1	"	.510	1.001	.209	III	8,991	64.0		0.80			
7C7-2	"	.511	1.014	.202	I	15,409	101.4		1.21			
7C7-3	"	.510	1.003	.256	I	12,714	105.1	90.2	1.25	0.34	1.5	0.6

TABLE A-12 (Cont'd)

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
7A5-1	-50	.533	1.005	.263	III	5,325	40.8		0.45			
7A5-2	"	.533	1.006	.198	III	6,228	41.9		0.47			
7A5-3	"	.531	.991	.259	III	5,880	46.2	43.0	0.52	0.06	9.1	4.1
7B5-1	"	.502	.989	.252	III	6,038	49.6		0.55			
7B5-2	"	.502	1.002	.240	III	6,547	50.7		0.55			
7B5-3	"	.512	1.004	.234	II	5,074	34.2	44.8	0.38	0.06	7.9	3.8
7C5-1	"	.511	1.002	.310	III	6,149	56.5		0.72			
7C5-2	"	.511	.983	.277	III	5,630	49.4		0.63			
7C5-3	"	.511	1.002	.223	III	6,547	47.7	51.2	0.61	0.82	6.3	3.4
7A1-1	-100	.532	1.005	.206	III	6,843	45.2		0.49			
7A1-2	"	.531	1.013	.267	III	5,315	40.6		0.44			
7A1-3	"	.533	.991	.217	III	6,251	43.6	43.1	0.48	0.06	9.2	4.0
7B1-1	"	.511	1.001	.234	III	8,788	66.4		0.69			
7B1-2	"	.501	.989	.212	III	6,278	46.3		0.49			
7B1-3	"	.502	1.002	.211	III	6,176	44.0	52.2	0.46	0.07	6.6	2.9
7C1-1	"	.511	1.014	.211	III	6,325	43.2		0.48			
7C1-2	"	.500	1.013	.127	III	9,316	50.3		0.59			
7C1-3	"	.531	1.014	.207	III	7,149	46.7	46.7	0.51	0.07	7.5	2.7

TABLE A-13

SUMMARY OF SMOOTH TENSILE PROPERTIES, 17-7PH, CODE 7

Specimen	Test Temp.(°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
7A2	200	174.5	162.5	8.0	36.7
7B2	200	174.2	161.5	7.0	16.8
7C2	200	176.8	157.6	11.5	36.5
7A7	75	183.1	164.0	10.0	32.4
7B7	75	198.2	181.3	10.0	25.7
7C7	75	187.1	156.6	10.0	36.4
7A7T1	75	186.8	166.7	11.0	28.8
7A7T2	75	185.7	159.5	10.0	34.2
7A7T3	75	175.9	153.4	14.0	39.2
7A5	-50	199.7	177.8	10.0	31.8
7B5	-50	201.3	178.9	12.0	29.9
7C5	-50	190.1	154.7	14.0	38.4
7A1	-100	205.9	180.3	11.0	30.6
7B1	-100	212.6	190.1	11.0	27.6
7C1	-100	207.1	179.8	11.0	31.8

TABLE A-14

FRACTURE TOUGHNESS DATA 17-7PH STEEL, CODE 8, FOUR-POINT LOADING, MAJOR SPAN = 5"; MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n/σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
8A2-1	200	.197	1.002	.246	I	7,010	114.9		1.22			
8A2-2	"	.198	1.003	.270	I	6,454	113.9		1.21			
8A2-3	"	.197	.961	.220	I	6,362	109.3	112.7	1.19	0.40	0.5	0.6
8B2-1	"	.204	.983	.226	II	4,945	89.0		1.04			
8B2-2	"	.202	1.003	.291	II	4,019	66.1		0.79			
8B2-3	"	.204	1.001	.255	II	4,945	92.5	82.5	1.07	0.25	0.8	1.0
8C2-1	"	.221	1.001	.252	II	6,195	107.4		1.24			
8C2-2	"	.221	.982	.230	I	6,297	107.4		1.25			
8C2-3	"	.223	.981	.211	II	7,325	119.6	111.5	1.37	0.46	0.5	0.5
8A7-1	75	.198	.989	.227	I	2,222	62.0		0.69			
8A7-2	"	.198	.989	.224	I	2,130	59.2		0.67			
8A7-3	"	.198	.998	.244	I	2,685	62.9	61.4	0.71	0.12	1.5	2.0
8B7-1	"	.205	.964	.185	I	3,519	66.3		0.81			
8B7-2	"	.203	.963	.211	II	2,593	61.6		0.75			
8B7-3	"	.202	.963	.220	II	2,408	61.7	63.2	0.75	0.15	1.4	1.4
8C7-2	"	.223	1.001	.246	I	4,537	55.6	55.6	0.69	0.12	2.0	2.1
8A5-1	-50	.197	.968	.216	III	3,273	58.5		0.65			
8A5-3	"	.197	.963	.215	III	3,343	60.3	59.4	0.67	0.10	1.7	2.0
8B5-1	"	.205	.962	.190	III	2,898	47.6		0.59			
8B5-2	"	.202	.934	.196	III	2,861	51.8		0.65			
8B5-3	"	.203	.963	.191	III	3,292	54.9	51.4	0.68	0.10	2.1	2.0
8C5-1	"	.223	.968	.204	III	2,449	37.8		0.45			
8C5-2	"	.222	1.004	.242	III	2,352	37.4		0.44			
8C5-3	"	.220	1.006	.269	III	2,514	53.8	43.0	0.51	0.07	3.4	3.6

TABLE A-14 (Cont'd)

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
8A1-1	-100	.197	.988	.225	III	2,820	49.4		0.56			
8A1-2	"	.197	.910	.180	III	2,607	47.6		0.53			
8A1-3	"	.197	.961	.263	III	2,116	43.6	46.9	0.44	0.06	3.0	3.1
8B1-1	"	.205	.927	.180	III	2,533	42.7		0.52			
8B1-2	"	.202	.964	.216	III	2,662	46.8		0.54			
8B1-3	"	.204	.930	.201	III	3,116	55.9	48.5	0.64	0.08	2.2	2.4
8C1-1	"	.221	1.002	.256	III	1,926	32.0		0.40			
8C1-2	"	.222	.981	.228	III	2,023	32.3		0.42			
8C1-3	"	.222	1.002	.252	III	2,019	32.8	32.4	0.42	0.03	5.9	7.3

TABLE A-15

SUMMARY OF SMOOTH TENSILE PROPERTIES, 17-7PH, CODE 8

Specimen	Test Temp. (°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)
8A2	200	178.9	177.2	17.0
8B2	200	170.9	164.0	17.0
8C2	200	177.2	162.6	18.0
8A7	75	188.2	173.0	17.5
8B7	75	179.0	163.7	18.0
8C7	75	187.9	164.3	18.5
8A5	-50	201.6	182.9	17.5
8B5	-50	189.1	161.6	18.5
8C5	-50	201.1	167.9	16.0
8A1	-100	207.3	186.0	20.0
8B1	-100	198.9	168.3	17.5
8C1	-100	207.8	175.5	17.5

TABLE A-16

FRACTURE TOUGHNESS DATA 17-7PH STEEL, CODE 9, FOUR-POINT LOADING, MAJOR SPAN = 5"; MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n/σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
9A7-1	75	.533	.975	.269	III	7,880	66.2		0.69			
9A7-2	"	.531	.975	.193	II	13,196	92.6		0.95			
9A7-3	"	.533	.975	.245	III	7,744	60.8	73.2	0.63	0.16	3.3	1.4
9B7-1	"	.533	.975	.245	III	10,214	87.2		0.94			
9B7-2	"	.504	.975	.220	II	12,038	11.5		1.18			
9B7-3	"	.508	1.003	.291	II	12,270	111.0	104.6	1.17	0.33	1.5	.77
9C7-1	"	.508	1.003	.236	III	7,121	61.7		0.69			
9C7-2	"	.511	1.003	.193	III	10,075	68.0		0.76			
9C7-3	"	.511	1.003	.186	III	10,612	70.3	66.6	0.79	0.15	3.5	1.4

TABLE A-17

SUMMARY OF SMOOTH TENSILE PROPERTIES, 17-7PH, CODE 9

Specimen	Test Temp. (°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
9A7-1	75	198.2	183.4	10.0	30.4
9B7-1	75	199.6	181.1	13.5	38.7
9B7-2	75	197.5	179.8	13.5	39.9
9C7	75	198.7	175.7	15.0	37.0

TABLE A-18

FRACTURE TOUGHNESS DATA 17-7PH STEEL, CODE 10, FOUR-POINT LOADING, MAJOR SPAN = 5"; MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
10A7-1	75	.611	.617	.153	I	43,522	68.9		0.83			
10A7-2	"	.609	.617	.142	I	45,374	76.9		0.92			
10A7-3	"	.609	.616	.118	III	51,393	61.0	68.9	0.75	0.11	5.5	1.3
10B7-2	"	.610	.615	.152	II	44,448	77.2	77.2	1.10	0.13	4.7	1.1
10C7-1	"	.611	.622	.152	II	41,670	69.1		0.97			
10C7-2	"	.618	.610	.116	II	39,818	67.5		0.96			
10C7-3	"	.622	.610	.143	II	39,818	70.0	68.9	0.99	0.10	5.8	1.3

TABLE A-19

SUMMARY OF SMOOTH TENSILE PROPERTIES, 17-7PH, CODE 10

Specimen	Test Temp. ($^{\circ}F$)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
10A7-1	75	222.3	206.4	13.5	35.8
10A7-2	75	223.1	206.7	15.0	36.5
10B7-2	75	220.6	210.8	14.0	41.9
10C7-2	75	224.3	213.2	14.0	37.6

TABLE A-20

FRACTURE TOUGHNESS DATA, PH 15-7 MO, STEEL, CODE 11, FOUR-POINT LOADING, MAJOR SPAN = 5"; MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
11A2-1	200	.515	.995	.285	III	14,380	117.8		1.20			
11A2-2	"	.515	1.002	.342	II	12,214	112.9	115.4	1.18	0.39	1.4	.54
11A7-1	75	.508	1.006	.238	III	9,149	69.5		0.70			
11A7-2	"	.518	1.007	.293	III	10,640	92.5	81.0	0.92	0.17	2.9	1.5
11A7t-2	"	.518	1.002	.227	III	9,346	69.1		0.74			
11A7t-3	"	.515	1.002	.287	III	9,047	78.3	73.7	0.84	0.16	3.1	1.5
11B7-1	"	.519	1.001	.303	III	9,186	80.5		1.03			
11B7-2	"	.518	1.003	.210	II	10,742	75.8		0.93			
11B7-3	"	.518	1.002	.250	II	10,500	69.2	75.2	0.86	0.24	2.2	1.1
11A5-1	-50	.515	1.006	.381	III	5,033	53.6		0.56			
11A5-2	"	.517	.998	.232	III	7,593	56.4		0.56			
11A5-3	"	.524	1.000	.191	III	8,177	48.2	52.7	0.47	0.67	7.8	4.0
11B5-1	"	.519	1.006	.229	II	6,991	45.7		0.49			
11B5-2	"	.518	1.014	.269	II	6,334	45.4	45.6	0.48	0.06	8.5	4.1
11A1-1	-100	.516	.998	.237	III	5,380	40.4		0.39			
11A1-2	"	.517	1.002	.280	III	5,352	44.5		0.44			
11A1-3	"	.505	1.006	.284	III	6,676	57.0	47.3	0.56	0.06	9.1	4.8
11B1-1	"	.519	1.014	.260	III	5,575	42.8		0.41			
11B1-2	"	.519	.995	.282	III	6,149	52.0		0.51			
11B1-3	"	.524	1.000	.210	III	7,093	43.8	46.2	0.43	0.05	10.0	5.4

TABLE A-21

SUMMARY OF SMOOTH TENSILE PROPERTIES, PH 15-7 Mo, CODE 11

Specimen	Test Temp. °F	F_{TU} (Ksi)	F_{TY} Ksi)	% Elong. (1" G.L.)	% Red. in Area
11A2	200	193.2	185.5	6.5	26.6
11B2	200	174.9	166.2	8.0	32.4
11A7	75	205.0	195.1	8.5	33.2
11A7T	75	190.1	183.3	5.0	30.0
11B7	75	194.0		13.5	34.4
11B7T	75	205.7	196.2	9.5	28.1
11A5	-50	212.9	203.2	8.0	28.0
11B5	-50	192.8	183.5	7.0	31.3
11A1	-100	206.7	199.7	7.0	32.8
11B1	-100	212.9	203.4	9.5	27.3

TABLE A-22

FRACTURE TOUGHNESS DATA PH 15-7 Mo STEEL, CODE 12, FOUR-POINT LOADING, MAJOR SPAN = 5"; MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n/σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
12A2-1	200	.525	.960	.300	II	10,251	90.8		0.92			
12A2-2	"	.521	.985	.315	II	9,806	84.4		0.85			
12A2-3	"	.524	1.002	.262	II	12,121	88.1	87.8	0.87	0.20	2.7	1.5
12B2-1	"	.522	1.006	.213	II	9,927	62.2		0.63			
12B2-2	"	.522	.998	.225	II	10,149	67.0		0.68			
12B2-3	"	.522	1.004	.347	II	7,380	65.7	65.0	0.69	0.11	4.4	2.3
12A7-1	75	.520	1.001	.257	II	6,213	44.1		0.42			
12A7-2	"	.521	1.006	.257	III	6,679	46.8		0.44			
12A7-3	"	.520	.980	.197	II P	6,195	36.4	42.4	0.35	0.04	11.7	5.6
12B7-1	"	.522	1.006	.276	II	6,741	49.5		0.48			
12B7-2	"	.522	.977	.236	II	5,352	37.6		0.37			
12B7-3	"	.522	.1001	.299	II	6,417	50.6	45.9	0.49	0.05	10.4	5.4
12A5-1	-50	.524	1.002	.260	III	4,204	29.6		0.27			
12A5-2	"	.527	.988	.159	III	4,579	24.7		0.23			
12A5-3	"	.524	.999	.196	III	5,024	29.9	28.1	0.27	0.02	22.7	8.7
12B5-1	"	.524	1.001	.320	III	3,787	31.2		0.28			
12B5-2	"	.523	1.001	.205	III	4,811	29.4		0.26			
12B5-3	"	.522	.978	.234	III	4,607	32.1	30.9	0.25	0.02	28.0	13.4
12A1-1	-100	.518	1.002	.306	III	3,477	27.9		0.26			
12A1-2	"	.524	1.002	.389	III	3,676	35.8	31.9	0.34	0.02	28.0	19.3
12B1-1	"	.522	1.001	.300	III	3,723	28.3		0.25			
12B1-2	"	.522	.981	.307	III	3,760	31.5		0.27			
12B1-3	"	.524	1.002	.245	III	4,144	28.1	29.3	0.24	0.02	31.5	17.2

TABLE A-23

SUMMARY OF SMOOTH TENSILE PROPERTIES, PH 15-7Mo, CODE 12

Specimen	Test Temp. (°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
12A2	200	223.6	196.1	9.5	32.8
12B2	200	217.6	191.6	8.5	28.5
12A7	75	235.5	206.8	11.0	30.9
12B7	75	230.0	203.4	11.0	23.4
12A5	-50	246.2	217.8	11.0	27.3
12B5	-50	243.8	222.4	10.0	11.3
12A1	-100	Broke in Threads			
12B1	-100	250.3	231.6	11.5	22.8

TABLE A-24

FRACTURE TOUGHNESS DATA, PH 15-7 Mo STEEL, CODES 13 and 14, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n/σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
13A7-1	75	.754	.755	.203	I	4,400	64.6		.90			
13A7-2	"	.754	.754	.228	I	3,950	63.4		.89			
13A7-3	"	.753	.754	.173	I	4,800	63.5	63.8	.88	.16	4.7	1.2
13B7-1	"	.749	.746	.232	I	3,700	62.1		.88			
13B7-2	"	.749	.750	.251	I	3,800	67.7		.95			
13B7-3	"	.749	.749	.179	III	4,300	59.1	63.0	.83	.16	4.7	1.4
14A7-1	"	.755	.755	.300	II	2,965	60.4		.82			
14A7-2	"	.754	.754	.267	III	2,710	49.2		.65			
14A7-3	"	.755	.754	.151	III	4,150	49.8	53.1	.65	.09	8.0	1.6
14B7-1	"	.749	.749	.236	III	3,630	60.9		.78			
14B7-2	"	.749	.749	.201	III	2,945	43.2		.55			
14B7-3	"	.750	.750	.168	III	3,630	47.1	50.4	.60	.08	9.3	2.1

TABLE A-25

SUMMARY OF SMOOTH TENSILE PROPERTIES, PH15-7Mo, CODES 13 & 14

Specimen	Test Temp. (°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
13A7	75	176.0*			
13B7	75	180.0*			
14A7	75	185.5	173.3	14.0	49.2
14B7-2	75	187.8	177.8	13.0	49.0

* Taken from Hardness Readings.

TABLE A-26

FRACTURE TOUGHNESS DATA 17-4 PH STEEL, CODE 15, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
15A2-1	200	.509	.893	.212	I	15,649	141.8		1.67	.85	.60	.25
15A2-2	"	.510	.999	.277	II	17,677	149.6		1.68	.95	.54	.29
15A2-3	"	.510	1.056	.302	IIP	8,519	62.2	117.9	0.74	.164	3.1	1.8
15B2-1	"	.515	1.006	.300	IIP	9,723	79.2		0.95	.257	2.0	1.2
15B2-2	"	.517	1.005	.304	IIP	10,408	85.8		1.03	.302	1.7	1.0
15B2-3	"	.512	1.015	.307	IIP	9,538	77.7	80.9	0.94	.247	2.1	1.2
15A7-1	75	.510	1.030	.311	III	5,454	47.0		0.61	.084	6.1	3.7
15A7-2	"	.508	1.026	.298	III	5,500	46.4		0.60	.081	6.2	3.6
15A7-3	"	.512	.999	.435	III	3,639	45.3	46.2	0.66	.078	6.6	5.6
15A7t-1	"	.509	1.042	.305	III	4,324	35.6		0.46	.040	12.6	7.6
15A7t-2	"	.509	1.049	.330	III	4,019	34.5		0.45	.038	13.4	8.7
15A7t-3	"	.510	1.032	.314	III	4,426	37.9	36.0	0.50	.046	11.1	6.8
15B7-1	"	.514	.991	.328	III	3,852	37.2		0.50	.044	11.6	7.4
15B7-2	"	.515	.990	.333	III	3,880	38.1		0.51	.046	11.2	7.2
15B7-3	"	.519	1.003	.288	III	4,158	35.0	36.8	0.46	.039	13.32	7.39
15B7t-1	"	.514	.995	.297	III	5,037	44.8		0.59	.148	3.5	2.0
15B7t-2	"	.528	..995	.330	III	3,773	35.5	40.1	0.48	.093	5.7	3.6
15B5-1	-50	.515	1.003	.310	III	3,676	32.9		0.31	.029	17.9	10.8
15B5-2	"	.511	1.038	.384	III	2,463	24.2		0.21	.015	33.0	24.8
15B5-3	"	.514	1.034	.316	III	3,047	25.9	27.7	0.26	.018	28.8	17.7
15A5-1	"	.509	1.058	.302	III	4,412	34.8		0.37	.037	13.7	8.1
15A5-2	"	.516	1.065	.296	III	3,676	27.7		0.29	.024	21.9	12.6
15A5-3	"	.515	1.055	.301	III	3,144	24.4	28.9	0.26	.018	28.1	16.1
15A1-1	-100	.517	1.067	.292	III	2,829	21.0		0.21	.013	40.4	22.8
15A1-2	"	.514	1.062	.292	III	3,019	22.9		0.23	.015	33.9	19.3
15A1-3	"	.509	1.064	.301	III	3,422	26.3	23.4	0.27	.020	25.2	14.9
15B1-1	"	.522	1.026	.333	III	2,917	25.8		0.27	.016	32.6	20.8
15B1-2	"	.515	1.023	.348	III	3,010	28.2	27.0	0.30	.019	27.3	18.2

TABLE A-27

SUMMARY OF SMOOTH TENSILE PROPERTIES, 17-4PH, CODE 15

Specimen	Test Temp. °F	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
15A2	200	179.1	148.1	15.0	55.3
15B2	200	190.0	161.0	12.0	40.5
15A7	75	191.6	167.7	13.0	54.8
15B7	75	196.6	170.1	13.0	45.5
15A5	-50	207.9	182.8	18.0	54.6
15B5	-50	216.7	189.0	16.0	41.5
15A1	-100	214.3	189.8	18.5	53.6
15B1	-100	220.6	194.5	16.0	41.8

TABLE A-28

FRACTURE TOUGHNESS DATA 17-4 PH STEEL, CODE 16, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
16A7-1	75	.635	.638	.220	III	6,195	103.2		1.38	.296	2.1	.74
16A7-2	"	.636	.638	.224	III	5,649	94.5		1.28	.248	2.6	.89
16A7-3	"	.636	.637	.222	III	6,612	112.4	103.3	1.49	.351	1.8	.63
16B7-1	"	.631	.634	.228	III	4,084	72.6		0.97	.121	5.2	1.9
16B7-2	"	.640	.636	.255	III	2,871	52.0		0.76	.062	10.3	4.1
16B7-3	"	.636	.636	.215	III	3,260	51.0	58.5	0.71	.060	10.7	3.6

TABLE A-29

SUMMARY OF SMOOTH TENSILE PROPERTIES, 17-4PH, CODE 16

Specimen	Test Temp.(°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
16A7	75	205.0	189.7	18.0	58.1
16B7	75	209.7	209.0	18.0	56.2

TABLE A-30

FRACTURE TOUGHNESS DATA FOR AM 355 STEEL, CODE 17, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
17A2-1	200	.774	.791	.187	I	5,820	71.6		1.01			
17A2-2	"	.774	.792	.139	I	5,500	56.1		.82			
17A2-3	"	.773	.790	.159	I	7,340	83.4	70.4	1.17	.213	3.6	.76
17B2-1	"	.772	.793	.199	I	5,650	72.3		1.02			
17B2-2	"	.772	.792	.230	I	4,520	63.9		.91			
17B2-3	"	.770	.754	.093	I	7,450	70.9	69.0	1.09	.205	3.8	.85
17A7-1	75	.774	.793	.225	I	7,300	96.6		1.29			
17A7-2	"	.774	.792	.221	I	4,500	69.5		.94			
17A7-3	"	.774	.791	.133	I	7,100	82.3	82.8	1.09	.225	3.4	.59
17A7t-1	"	.785	.789	.250	I	6,100	85.4		1.12			
17A7t-2	"	.789	.790	.252	I	6,300	86.4		1.13			
17A7t-3	"	.785	.789	.179	I	12,200	130.8	100.9	1.66	.329	2.4	.54
17B7-1	"	.769	.792	.250	I	5,600	86.2		1.11			
17B7-2	"	.771	.795	.252	I	4,400	66.2		.87			
17B7-3	"	.771	.793	.179	I	7,400	89.4	80.6	1.14	.203	3.8	.88
17A5-1	-50	.774	.791	.234	III	5,340	74.1		.65			
17A5-2	"	.775	.791	.220	III	6,490	85.5		.75			
17A5-3	"	.774	.793	.184	III	8,100	94.0	84.4	.82	.226	3.4	.94
17B5-1	"	.772	.793	.220	I	5,200	68.5		.58			
17B5-2	"	.772	.793	.237	I	5,880	82.1		.70			
17B5-3	"	.768	.792	.171	I	7,700	87.0	79.2	.74	.205	3.8	1.0
17B1-1	-100	.772	.791	.220	III	4,190	56.7		.68			
17B1-2	"	.774	.792	.226	II	4,505	62.1		.74			
17B1-3	"	.774	.793	.141	III	6,910	71.1	63.3	.86	.119	6.5	1.6
17A1-1	"	.776	.792	.246	I	3,390	49.5		.61			
17A1-2	"	.773	.793	.233	I	4,180	58.7		.72			
17A1-3	"	.774	.792	.159	III	6,100	67.0	58.4	.82	.105	7.4	2.0

Table A-31

SUMMARY OF SMOOTH TENSILE PROPERTIES, AM 355 STEEL, CODE 17

Specimen	Test Temp. °F	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
17A2	200	165.2	152.5	14.0	57.2
17B2	200	166.0	152.4	17.0	62.8
17A7	75	174.7	162.2	18.0	59.0
17B7	75	178.9	166.7	17.0	55.8
17A7t-1	75	176.0	164.4	17.0	59.0
17A7t-2	75	176.8	161.7	19.0	57.5
17A5	-50	196.1	177.6	20.0	53.9
17B5	-50	194.3	174.9	20.0	58.4
17A1	-100	197.7	180.3	20.0	56.5
17B1	-100	203.1	183.2	18.0	54.1

TABLE A-32

FRACTURE TOUGHNESS DATA FOR AM 355 STEEL, CODE 18, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
18A7-1	75	.654	1.003	.310	III	5,700	69.6		.796			
18A7-2	"	.661	1.002	.326	III	5,700	72.1		.827			
18A7-3	"	.654	1.001	.170	I	9,520	80.2	74.0	.925	.168	3.9	1.0
18B7-1	"	.769	.800	.196	III	6,300	78.8		1.054			
18B7-2	"	.770	.795	.215	I	6,000	81.2		1.087			
18B7-3	"	.770	.794	.163	III	11,400	138.5	99.5	1.745	.388	2.0	.42

TABLE A-33

SMOOTH TENSILE PROPERTIES, AM 355 STEEL, CODE 18

Specimen	Test Temp. (°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
18A7-1	75	179.2	170.2	15.0	46.0
18A7-2	75	181.6	171.9	15.0	44.4
18B7	75	169.1	159.8	19.0	60.8

TABLE A-34

FRACTURE TOUGHNESS DATA AM-355 STEEL, CODE 19, FOUR-POINT LOADING, MAJOR SPAN = 5"; MINOR SPAN = 2-1/2"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n/σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
19A2-1	200	.625	.619	.150	I	9,816	129.6		1.80			
19A2-2	"	.628	.618	.126	I	10,371	122.2		1.72			
19A3-3	"	.636	.619	.145	I	10,093	128.6	126.8	1.78	0.63	1.0	0.2
19B-1	"	.632	.619	.122	I	11,945	142.6		1.98			
19B2-2	"	.630	.618	.122	I	11,112	129.9		1.85			
19B2-3	"	.628	.618	.115	I	11,112	126.0	132.8	1.81	0.73	0.8	0.2
19A7-1	75	.640	.617	.134	I	12,797	160.2		2.02			
19A7-2	"	.631	.618	.144	I	12,251	152.9		1.93			
19A7-3	"	.630	.619	.116	I	12,316	132.9	148.7	1.74	0.76	0.8	0.2
19B7-1	"	.634	.618	.163	I	11,825	174.4		2.23			
19B7-2	"	.629	.618	.145	I	12,242	166.7		2.15			
19B7-3	"	.631	.619	.136	I	12,334	158.3	166.5	2.08	1.03	0.6	0.1
19A5-1	-50	.628	.617	.122	II	11,918	146.3		1.79			
19A5-2	"	.625	.618	.119	I	11,482	137.7		1.70			
19A5-3	"	.630	.617	.104	I	11,853	130.9	138.3	1.65	0.56	1.1	0.2
19B5-1	"	.635	.619	.118	III	9,834	110.2		1.35			
19B5-2	"	.638	.619	.122	II	11,714	137.6		1.63			
19B5-3	"	.637	.619	.127	III	11,149	133.3	127.0	1.59	0.04	1.4	0.3
19A1-1	-100	.629	.620	.136	III	7,714	92.6		1.20			
19A1-2	"	.632	.618	.135	III	6,667	78.7		1.04			
19A1-3	"	.633	.618	.130		5,852	66.7	79.3	0.89	0.19	3.4	0.7
19B1-1	"	.626	.619	.148	III	6,667	84.0		1.06			
19B1-2	"	.628	.618	.113	III	6,843	73.0		0.95			
19B1-3	"	.620	.632	.119	III	6,805	72.1	76.4	0.92	0.15	3.9	0.8

TABLE A-35

SUMMARY OF SMOOTH TENSILE PROPERTIES, AM 355, CODE 19

Specimen	Test Temp. °F	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G. L.)	% Red. in Area
19A2	200	171.8	159.9	15.0	55.1
19B2	200	168.3	155.7	14.0	58.5
19A7	75	183.0	171.7	15.0	52.6
19B7	75	174.1	162.9	17.0	56.3
19A5	-50	192.2	174.5	20.0	53.8
19B5	-50	200.8	183.6	16.0	52.3
19A1	-100	197.4	176.5	17.0	50.8
19B1	-100	200.2	182.3	18.0	53.1

TABLE A-36

FRACTURE TOUGHNESS DATA FOR BETA TITANIUM, CODE 20, THREE-POINT LOADING, MAJOR SPAN = 5"

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n/σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
20A2-1	200	.997	1.000	.303	III	7,710	61.1		.804			
20A2-2	"	.996	.957	.245	III	9,000	67.7		.901			
20A2-3	"	1.003	1.008	.200	III	11,600	68.4	65.7	.895	.196	5.1	1.3
20B2-1	"	1.001	1.001	.362	III	6,310	58.4		.821			
20B2-2	"	.999	1.000	.287	III	7,040	53.2		.737			
20B2-3	"	1.002	.999	.219	III	9,700	61.3	57.5	.846	.166	6.0	1.7
20C2-1	"	.995	.999	.259	I	8,760	62.3		.874			
20C2-2	"	1.005	1.003	.332	I	7,700	65.3		.925			
20C2-3	"	.992	1.001	.205	I	9,640	63.6	63.7	.897	.213	4.6	1.2
20A7-1	75	.945	1.119	.284	III	7,300	44.0		.561			
20A7-2	"	1.110	1.002	.295	III	6,300	47.6		.631			
20A7-3	"	.999	.995	.191	III	8,100	47.3	46.3	.635	.098	10.2	1.9
20A7t-1	"	1.001	1.003	.294	II	5,700	43.2		.573			
20A7t-2	"	1.003	.989	.307	II	5,100	41.2		.553			
20A7t-3	"	1.004	.986	.190	II	7,160	42.1	42.2	.570	.081	12.4	2.3
20B7-1	"	.952	1.106	.437	III	5,500	49.4		.630			
20B7-2	"	..992	.999	.260	III	6,300	44.3		.568			
20B7-3	"	.903	.993	.205	III	7,050	47.5	47.1	.614	.094	10.5	2.2
20B7t-1	"	1.004	1.003	.276	I	8,420	61.1		.754			
20B7t-2	"	.999	1.001	.233	I	7,950	25.3		.318			
20B7t-3	"	.898	1.002	.199	II	8,250	25.3	37.2	.320	.056	18.0	3.6
20C7-1	"	.918	1.099	.303	III	6,200	42.6		.566			
20C7-2	"	1.005	1.003	.391	III	5,520	54.0		.778			
20C7-3	"	1.003	1.001	.197	III	9,700	57.2	51.3	.794	.132	7.6	1.5

TABLE A-36 (Cont'd)

Specimen	Test Temp. °F	Thick B,(in)	Width W,(in)	Crack Length (a) (in)	Curve Type	Load (lbs)	Fracture Toughness (K_{IC} Ksi $\sqrt{in}$)	AVE.	σ_n / σ_y	Ratio (R) $(K/\sigma_y)^2$	$\frac{B}{R}$	$\frac{a_o}{R}$
20C5-1	-50	1.005	1.003	.337	III	6,640	56.1		.632			
20C5-2	"	1.001	1.001	.267	III	7,490	53.0		.589			
20C5-3	"	1.006	1.003	.226	III	7,940	49.8	53.0	.555	.090	11.2	3.1
20A5-1	"	1.003	.992	.348	III	5,215	46.5		.508			
20A5-2	"	1.003	1.006	.274	III	6,300	44.7	45.6	.475	.061	16.5	5.1
20B5-1	"	.995	.997	.376	III	4,200	40.1		.470			
20B5-2	"	1.003	.997	.260	III	5,670	39.4		.447			
20B5-3	"	1.002	1.003	.205	III	7,070	41.8	40.5	.475	.054	18.7	5.2
20A1-1	-100	1.000	1.003	.260	III	6,970	48.1		.512			
20A1-2	"	1.000	1.009	.261	III	6,950	47.3		.504			
20A1-3	"	1.003	.957	.184	III	7,010	43.0	46.2	.474	.062	16.0	3.8
20B1-1	"	.999	.999	.304	III	5,240	41.1		.466			
20B1-2	"	.999	.999	.297	III	5,150	39.5*		.449			
20B1-3	"	.999	1.000	.197	III	7,920	46.3	42.3	.528	.059	17.1	4.5
20C1-1	"	1.005	1.000	.201	III	8,930	52.7		.603			
20C1-2	"	1.003	1.000	.307	III	7,420	58.6		.667			
20C1-3	"	.998	.997	.208	III	8,050	49.0	53.5	.561	.095	10.5	2.5

TABLE A-37

SUMMARY OF SMOOTH TENSILE PROPERTIES, Ti6Al-4V, CODE 20

Specimen	Test Temp.(°F)	F_{TU} (Ksi)	F_{TY} (Ksi)	% Elong. (1" G.L.)	% Red. in Area
20A2	200	159.1	148.4	5.0	6.9
20B2	200	153.7	141.0	2.5	1.6
20C2	200	152.6	138.0	3.0	7.3
20A7	75	156.7	--	--	--
20B7	75	174.9	167.2	2.0	5.3
20C7	75	169.2	157.9	2.0	6.3
20A5	-50	143.9	--	--	--
20B5	-50	176.1	174.8	0.5	--
20C5	-50	188.8	176.7	2.0	2.1
20A1	-100	189.8	185.0	0.5	.6
20B1	-100	179.6	--	0.5	--
20C1	-100	184.3	173.2	3.0	4.9
20A7-1	75	156.6	148.2	14.0	45.5
20B7-1	75	162.5	153.6	19.0	40.4
20C7-1	75	154.1	141.3	12.0	39.6

TABLE A-38

SUMMARY OF LITERATURE DATA OF K_{IC} FOR LOW ALLOY MARTENSITIC STEELS

Material	Form	Test Orientation*	Test Temp. °F	Yield Strength(Ksi)	Tensile Strength(Ksi)	Specimen Type **	K_{IC} $K\sqrt{in.}$	Specimen Size (in) Thkns. B	Width W	Length L	$\left[\frac{K}{F_{TY}}\right]=R^2$	$\frac{B}{R}$	Ref.
4340	.070" sheet	L	-100	226.0	295.4	CN	32.8	.070	1.75	8	.021	3.3	8
"	"	L	-45	224.5	289.0	CN	36.0	.070	1.75	8	.026	2.7	8
"	"	L	-100	227.3	288.4	CN	35.8	.070	1.75	8	.025	2.8	8
"	.250" sheet	L	75	216.8	282.0	SEN	53.2	.147	1.00	4	.060	2.5	9
"	"	L	75	216.8	282.0	SEN	61.0	.145	1.00	4	.079	1.9	9
"	"	L	75	221.2	263.5	SEN	60.8	.147	1.00	4	.075	2.0	9
"	"	L	75	221.2	263.5	SEN	61.3	.147	1.00	4	.078	1.9	9
"	1" plate	L	75	213	222	NB3	70	1	2.2	18	.011	9.2	10
"	"	L	75	199	215	NB3	93	1	2.2	18	.022	4.5	10
"	0.250" sheet	L	RT	216.8	282	CN	51.3	0.150	2.000	8.00	.056	2.7	13
"	"	L	RT	216.8	282	CN	39.1	0.158	2.000	8.00	.032	5.0	13
"	"	L	RT	221.2	263	CN	53.5	0.150	2.000	8.00	.058	2.6	13
"	"	L	RT	208.9	263	CN	55.5	0.153	2.000	8.00	.070	2.2	13
"	0.625" sheet	L	RT	222.1	263	SEN	45.1	0.515	2.000	8.00		2.5	9
"	"	L	RT	222.1	263	SEN	50.0	0.523	2.000	8.00		"	9
"	"	L	RT	222.1	263	SEN	50.4	0.520	2.000	8.00		"	9
"	"	L	RT	216.0	254	SEN	53.5	0.523	2.000	8.00		"	9
"	"	L	RT	228.2	270	NB3	45.0	0.500	0.500	3.50		"	9
"	"	L	RT	228.2	270	NB3	47.0	0.500	0.500	3.50		"	9
"	"	L	RT	228.2	270	NB3	47.9	0.500	0.500	3.50		"	9
"	"	L	RT	216.1	254	NB3	40.3	0.500	0.500	3.50		"	9
"	"	L	RT	216.1	254	NB3	48.9	0.500	0.500	3.50		"	9
"	"	L	RT	216.1	254	NB3	49.1	0.500	0.500	3.50		"	9
"	1"-Dia. Bar		-100	225.4	290	NR	40.6	0.505	0.375	3.00		"	8
"	"		-45	224.4	286	NR	42.4	0.505	0.375	3.00		"	8
"	"		40	219.6	282	NR	52.5	0.505	0.375	3.00		"	8
"	"		75	221.0	281	NR	55.5	0.505	0.375	3.00		"	8
"	"		200	216.7	284	NR	48.3	0.505	0.375	3.00		"	8
"	"		300	195.0	289	NR	41.8	0.505	0.375	3.00		"	8
"	"		RT	238.0	280	NR	26.7	0.750	0.575	4.00		"	11
"	"		RT	238.0	280	NR	27.8	0.750	0.575	4.00		"	11
"	"		RT	236.0	265	NR	39.0	0.750	0.575	4.00		"	11
"	"		RT	236.0	265	NR	40.0	0.750	0.575	4.00		"	11

* L - Longitudinal
T - Transverse

** CN - Center Notch
SEN - Single Edge Notch
NB3 - Notch Bend, 3 pt. Loading
NR - Notch Round

TABLE A-38 (Continued)

Material	Form	Test Orientation*	Test Temp. °F.	Yield Strength(Ksi)	Tensile Strength(Ksi)	Specimen Type **	K_{IC} $K\sqrt{in.}$	Specimen Size (in.) Thkns. B	Width W	Length L	$\left[\frac{K}{F_{TY}}\right]^2 = R$	$\frac{B}{R}$	Ref.
4340	1"-Dia. Bar		RT	229.0	245	NR	47.0	0.750	0.575	4.00		2.5	11
"	"		RT	229.0	245	NR	46.8	0.750	0.575	4.00		"	11
"	"		RT	217.0	230	NR	61.5	0.750	0.575	4.00		"	11
"	"		RT	217.0	230	NR	55.5	0.750	0.575	4.00		"	11
"	1.25" Plate	L	RT	228.2	265	NB3	50.4	1.000	1.000	5.00		"	9
"	"	L	RT	228.2	265	NB3	49.7	1.000	1.000	5.00		"	9
"	"	L	RT	216.1	240	NB3	50.4	1.000	1.000	5.00		"	9
"	"	L	RT	216.1	240	NB3	54.5	1.000	1.000	5.00		"	9
"	"	L	RT	216.1	240	NB3	45.3	1.000	1.000	5.00		"	9

TABULATION OF K_{IC} DATA, FERROUS ALLOYS - H-11 STEEL

TABLE A-39

Material	Form	Test Orientation*	Test Temp. °F	Yield Strength(Ksi)	Tensile Strength(Ksi)	Specimen Type **	K_{IC} K $\sqrt{in.}$	Specimen Size(in) Thkns. B	Width W	Length L	$\left[\frac{K}{F_{TY}}\right]^2 = R$	$\frac{B}{R}$	Ref.
5Cr-Mo-V	0.085" sheet	L	-100	257.6	308.4	CC	25.4	0.085	1.750	8.00	.0095	9.0	8
"	"	L	-45	247.7	300.4	CC	24.5	0.085	1.750	8.00	.0097	10.0	8
"	"	L	40	240.2	291.6	CC	29.5	0.085	1.750	8.00	.015	5.6	8
"	"	L	75	242.9	291.5	CC	30.2	0.085	1.750	8.00	.015	5.5	8
"	"	T	75	235.2	286.8	CC	28.7	0.085	1.750	8.00	.015	5.6	8
"	"	L	200	231.6	281.8	CC	42.5	0.085	1.750	8.00	.0338	2.5	8
"	"	L	-100	240.2	280.4	CC	30.3	0.085	1.750	8.00	.0159	5.3	8
"	"	L	-45	231.4	270.8	CC	29.7	0.085	1.750	8.00	.0169	5.0	8
"	"	L	40	225.4	263.9	CC	35.1	0.085	1.750	8.00	.0243	3.3	8
"	"	L	75	223.2	261.6	CC	33.5	0.085	1.750	8.00	.0225	3.8	8
"	"	T	75	223.0	265.4	CC	36.9	0.085	1.750	8.00	.0274	3.1	8
"	"	L	-100	202.7	239.0	CC	37.4	0.085	1.750	8.00	.0339	2.5	8
"	"	L	-45	196.2	233.4	CC	33.5	0.085	1.750	8.00	.0292	2.9	8
"	1.00" Dia. Bar	L	-45	251.0	308.7	NR	21.7	D=0.375	d=0.375	3.00			8
"	"	L	40	216.0	301.5	NR	26.6	D=0.500	d=0.375	3.00			8
"	"	L	75	240.0	247.6	NR	25.0	D=0.500	d=0.375	3.00			8
"	"	L	200	226.0	286.9	NR	35.4	D=0.500	d=0.375	3.00			8
"	"	L	300	228.0	277.8	NR	40.4	D=0.500	d=0.375	3.00			8
"	"	L	-45	235.1	281.0	NR	27.3	D=0.500	d=0.375	3.00			8
"	"	L	40	228.2	273.0	NR	32.6	D=0.500	d=0.375	3.00			8
"	"	L	75	228.2	270.0	NR	34.8	D=0.500	d=0.375	3.00			8
"	"	L	200	219.7	263.8	NR	44.5	D=0.500	d=0.375	3.00			8
"	"	L	300	214.7	252.8	NR	49.0	D=0.500	d=0.375	3.00			8
"	"	L	-45	207.7	244.7	NR	44.0	D=0.500	d=0.375	3.00			8
"	8.00" Square Forged Billet	T	RT	225.0	270	NB3	38.0	0.750	0.750	3.50			9
"	"	T	RT	225.0	270	NB3	39.3	0.750	0.750	3.50			9
"	"	T	RT	225.0	270	NB3	37.3	0.750	0.750	3.50			9
"	"	T	RT	225.0	270	NB3	45.0	0.750	0.750	3.50			9
"	"	T	RT	225.0	270	NB3	33.7	0.750	0.750	3.50			9
"	"	T	RT	225.0	270	NB3	37.1	0.750	0.750	3.50			9
"	"	T	RT	225.0	270	NB3	35.4	0.750	0.750	3.50			9
"	"	T	RT	225.0	270	NB3	38.1	0.750	0.750	3.50	.028	26.0	9
"	"	T	RT	194.2	228	NB3	66.8	1.000	1.000	3.50			9
"	"	T	RT	194.2	228	NB3	73.1	1.000	1.000	3.50			9
"	"	T	RT	194.2	228	NB3	80.1	1.000	1.000	3.50			9
"	"	T	RT	194.2	228	NB3	71.2	1.000	1.000	3.50			9
"	"	T	RT	194.2	228	NB3	76.5	1.000	1.000	3.50			9
"	"	T	RT	194.2	228	NB3	78.7	1.000	1.000	3.50			9
"	"	T	RT	194.2	228	NB3	61.6	1.000	1.000	3.50			9

* L - Longitudinal
T - Transverse

** CN - Center Notch
SEN - Single Edge Notch
NB3 - Notch Bend, 3 pt. Loading
NR - Notch Round

TABLE A-39 (Cont'd)

Material	Form	Test Orientation*	Test Temp. °F	Yield Strength(Ksi)	Tensile Strength(Ksi)	Specimen Test **	K_{IC} K $\sqrt{in.}$	Specimen Size(in) Thkns. B	Width W	Length L	$\left[\frac{K}{F_{TY}}\right]^2 = R$	$\frac{B}{R}$	Ref.
5Cr-Mo-V	8.00" Square Forged Billet	T	RT	194.2	228	NB3	61.6	1.000	1.000	3.50			9
"	"	T	RT	194.2	228	NB3	77.6	0.750	0.750	3.50	.140	5.5	9
"	"	L	RT	221.2	280	NB3	45.0						9
"	"	L	RT	221.2	280	NB3	38.5						9
"	"	L	RT	221.2	280	NB3	38.3						9
"	"	L	RT	221.2	280	NB3	39.8					2.5	9
"	"	L	RT	221.2	280	NR	21.5	D=0.500	d=0.357	3.00			9
"	"	L	RT	221.2	280	NR	24.0	D=0.500	d=0.357	3.00			9
"	"	L	RT	221.2	280	NR	17.6	D=0.500	d=0.357	3.00			9
"	"	L	RT	221.2	280	NR	34.4	D=0.500	d=0.357	3.00			9
"	"	L	RT	221.2	280	NR	27.4	D=0.500	d=0.357	3.00			9
"	"	L	RT	193.8	228	NB3	71.5						9
"	"	L	RT	193.8	228	NB3	88.0						9
"	"	L	RT	193.8	228	NB3	72.9						9
"	"	L	RT	193.8	228	NB3	61.9						9
"	"	L	RT	193.8	228	NB3	82.2						9
"	"	L	RT	193.8	228	NB3	88.4						9

TABLE A-40

TABULATION OF K_{IC} DATA, AM 355 STEEL

Material	Form	Test Orientation*	Test Temp. °F	Yield Strength(Ksi)	Tensile Strength(Ksi)	Specimen Type **	K $K\sqrt{in.}$	Specimen Size (in) Thkns. B	Width W	Length L	$\left[\frac{K}{F_{TY}}\right]^2 = R$	$\frac{B}{R}$	Ref.
	9.00" x 9.00" Billet		RT	198.4	229	NB	43.7	0.625	1.000	3.50			9
	"		RT	198.4	229	NB	42.5	0.625	1.000	3.50			9
	"		RT	198.4	229	NB	38.1	0.625	1.000	3.50	.043	14.4	9
	"		RT	201.1	224	NB	67.6	0.625	1.000	3.50			9
	"		RT	201.1	224	NB	80.9	0.625	1.000	3.50			9
	"		RT	201.1	224	NB	72.4	0.625	1.000	3.50	.135	4.6	9
	"		RT	206.8	235	NB	46.5	0.625	1.000	3.50	.056	11.0	9
	"		RT	201.1	224	NB	73.9	0.625	1.000	3.50			9
	"		RT	201.1	224	NB	77.3	0.625	1.000	3.50	.135	4.6	9
	"		RT	171.7	195	NB	76.2	0.625	1.000	3.50	.200	3.1	9

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13. ABSTRACT

An experimental program was conducted to determine the plane strain fracture toughness (K_{IC}) of the following classes of high-strength materials:

1. AISI Alloy Steels (4340, 4140)
2. 5Cr-Mo-V Steels
3. Precipitation-Hardening Stainless Steels (17-7 PH, PH 15-7 Mo, 17-4, AM 355)
4. Titanium Alloy, Ti-6Al-4V

The precracked notched bend test was used as the test method and several heats of each material were evaluated over a range of test temperatures from -100 to +200°F. The K_{IC} values, obtained under conditions which were believed to provide valid plane strain fracture toughness numbers, were compiled for possible presentation in handbook form. The method of presentation involved plotting K_{IC} both as a function of material strength and test temperature. The resulting curves provide representative K_{IC} figures which can aid in the selection of materials for reliable performance.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fracture Toughness						
High Strength Steel						
Titanium						

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